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Compressive properties of thin steel coupons

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COMPRESSIVE PROPERTIES OF THIN STEEL COUPONS

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TABLE OF CONTENTS

ABSTRACT

This report is part of the general project, "Built-Up Members in Plastic Design", and particularly pertains to the tests on longitudinally stiffened plate panels. It gives a summary of compression tests conducted on thin steel coupons made from the material used in the fabrication of the panels. The tests were conducted through the stress-strain curve including the strain hardening range.

In order that the goals of the tests could be achieved, it was necessary to develop two new pieces of testing equipment. These were a strain gage to measure large strains in the strain hardening range and a device, a compression jig, which gave lateral support to the thin coupons. The strain gage proved very effective in the plastic and strain hardening ranges.

The test results showed a yield stress in compression approximately 10% higher than the tensile value. The elastic modulus was the same in tension as in compression. The stress relieved coupons had a lower yield stress than the nonheat-treated coupons in compression as well as in tension. The compressive properties obtained in the plastic and strain hardening ranges had approximately the same magnitude and

scatter as the properties obtained in tension. The values of E_{st} and ε_{st} obtained in these regions compared favorably with the values obtained from the tension tests and were more consistent.

The compressive properties were found to be dependent on the direction of rolling, however, no consistent relationship could be established.

1. INTRODUCTION

At present the material properties of structural steel are usually found by performing tensile tests on steel coupons. In most cases the compressive properties of the steel are assumed equal to the tensile properties and hence these are used in all calculations.

Tests were performed on stiffened plates at Lehigh University to determine their strength*. An analysis was to be made to see how theory correlated with test results. In order to make the analysis, true properties of the material in compression were needed. A comparison was to be made between the properties (Fig. 1) obtained from tension and compression tests and if good correlation was observed future material properties would be determined only from tension tests, since they are much easier to make.

The testing was to be performed on material obtained from different parts of test panels, Figs. 2 and 3: a 1/4 in. thick plate, ST3B4.25, and a 6 Jr 4.4.

An investigation was also to be made on the effect of heat-treating on the properties of the material and on the directional properties of the material.

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* Project 248: Built-Up Members in Plastic Design

In order that the compression testing could be carried out, some means of lateral support had to be devised to prevent buckling of the thinner coupons. A description is presented herein of the development of a supporting device hereafter called a compression jig, Fig. 4.

As testing progressed, the scope of the desired properties widened and it was decided to also obtain the strain hardening strain ϵ_{st} and the strain hardening modulus E_{st} of the steel in compression. These values were to be compared with the corresponding values obtained from tensile tests.

Gages available for compression testing make this a difficult task. The gages are either undependable for the size of specimens used or else have a limited strain range. Other gages such as the Huggenberger strain gage require great care, and even then it is very difficult to avoid human error. A survey of available gages was made and it was decided that more satisfactory results could be obtained from an improved version of a gage previously used by Alfons Huber[1*]. This gage is called the Hubermeter in this paper.

A comparison was made between the tests performed with the more commonly used gages and equipment and the tests performed with the testing equipment developed in this project. It was found that truer yield stress values could be obtained

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* Numbers refer to material listed in references.

from the jig supported specimens. The Huggenberger gage performed the best in the elastic range, while the Hubermeter gave excellent results in the plastic and strain-hardening ranges.

2. TESTING APPARATUS

2.1 General

Three major requirements had to be fulfilled for the coupon testing: the coupon had to be prevented from buckling, the load had to be applied concentrically to the coupon, and a gage capable of giving strain values far into the strain hardening range had to be used. The setup used to achieve these goals is shown in Fig. 6. The coupon (1) is supported from buckling laterally by the compression jig (2), while the subpress (4) partially helps center the load. The strains are measured by the Hubermeter (3).

The problem of accurately measuring strains and small displacements is a difficult and fascinating one. Since the movements to be measured may be well below those which can be detected by the unaided eye, it is obvious that some sort of magnification of their effects is needed. The most obvious solution is to magnify the movements mechanically by a system of levers, or similar means. To design such a system seems at first glance to be easy. If one lever gives a magnification of ten to one, then a combination of two should give a magnification of one hundred to one and so on. Many problems not previously considered crop up when this procedure is tried. Factors such as friction, lost motion, the weight and inertia of the gage and flexibility begin to reduce to a great extent the reliability and magnification power of the gage. The difficulties increase rapidly with the degree of magnification.

Another method of measuring strains is with electrical gages. Of the electrical gages the resistance type is the most popular one. The theory of the resistance type of gage is to express a reading as the function of a resistance change produced by the displacement. Each gage length of wire is cemented to the coupon. The wires cannot buckle and need not be preloaded. The cement gives enough support so that the gage will respond to compression as well as tension. The principle of operation is based on the formula for the resistance of a conductor.

$$R = \rho \frac{L}{A}$$

R = resistance of conductor

ρ = specific resistance

L = length of conductor

A = cross-sectional area of conductor

The electrical gages needed for the compression coupons would have to be of short length and width. The gage would therefore be more sensitive to local variations of strain. Hence if local yield lines would occur beneath the gage the gage would not be giving the true strain in the whole coupon. This makes the electric resistance gage unusable beyond the yield point.

2.2 Hubermeter

As mentioned previously a gage similar to the one discussed herein was designed by A. Huber in 1951. He used his gage to measure compressive strains in the strain hardening range in order to obtain the strain hardening modulus.

The construction of the Hubermeter is based on a combination of electrical and mechanical gage principles. The method of design used is given in Fig. 6. The graphs in Figs. 7 and 8 were used to fix the final dimensions of the Hubermeter.

As shown in Fig. 6, the gage acts as a two hinged rectangular frame. A deflection of the supports towards each other causes bending moments in the beam, L_2. The bending strains are measured by two electrical resistance strain gages mounted on it. A definite relationship exists between the strains measured on the beam and the actual strains in the coupon. The Hubermeter was calibrated with a Templin calibrator, Fig. 10. A gage factor $\varepsilon/\varepsilon^* = 32.75$ was obtained which is in very good agreement with the theoretically computed value of 33.50, where ε is the strain in the coupon and ε^* is the sum of the absolute values of the bending strains at the center of the beam. Huber computed a theoretical gage factor of 94 and obtained a calibrated factor of 85.75.

The gage was connected to two rods on the calibrator, which were displaced a known distance. The gage factor is obtained from the known displacement and the SR-4 readings. Fig. 11 shows the values obtained from the calibrator. The parallel lines indicate that if loading and unloading is allowed, the gage contact points will slip.

The deflection of the bases is caused by the shortening of the gage length of the compression coupon, L_o. The change in length is transmitted to the frame by the four contact points, Fig. 9.

As the coupon strains, a force is developed on the screws which tends to force the gage contact points closer together. Small impressions may be made on the coupon to prevent slipping of the contact points. These impressions, however, should be made very small in comparison to the gage length. It is evident that the forces at the points as well as all other forces, such as gage weight should be kept as small as possible. The magnitude of forces developed on the contact points at the extreme of the testing range was one of the factors controlling the Hubermeter dimensions and selection of aluminum as the fabrication material.

The main design problem, however, was to proportion the Hubermeter so that a low gage factor could be obtained in order that a sufficient range of readings could be made on the strain indicator in the strain hardening range. The gage factor varies inversely with the force developed on the screws, hence, a design had to be made which most nearly satisfied both requirements, minimum force and a low gage factor.

Some other factors set limiting values on the gage dimensions; the gage was limited in width by the dimensions of the compression jig, Fig. 4 and the beam portion of the Hubermeter had to be of sufficient length and width to allow for the mounting of the strain gages. Also, it was desired to keep the Hubermeter gage as trim and compact as possible. The weight of the gage should be kept small and concentrated as close as possible to the surface of the specimen; if the gage is "top heavy", its weight may produce a strong tendency to tip it, thereby causing one set of contact points to slide laterally. The clamping pressure would then of necessity need to be increased to keep the minimum pressure adequate.

It has been found that the strain hardening modulus for steel can best be obtained in the region between the strain hardening, ε_{st}, and a strain of approximately 0.005 in./in. beyond ε_{st}[2]. These strains induced stresses of approximately 13,000 psi in the Hubermeter, which is well below the yield strength of the aluminum (2024 T-4 aluminum with σ_y = 47 ksi and $E_{AL} = 10x10^6$ psi). The Hubermeter was calibrated at this and higher stresses and the gage factor was found to remain a constant 32.75.

The Hubermeter was machined from a block 3in.x2in.x2in. Fabrication from one solid piece was necessary in order that the gage act as a rigid frame. Fabrication of the gage in parts would most likely have intorduced some lost motion at joint connections. The gage factor would than vary during testing and this is undesirable.

2.3 Huggenberger Extensometer and SR-4 Gages

The Huggenberger tensometer is a light weight self contained instrument, relying solely on a compound-lever system for magnification of displacements. Since even normal wear has a tendency to change the gage factor, the Huggenberger tensometer should be calibrated at frequent intervals. The gages used in the tests were calibrated before each test series. The two Huggenberger gages used in the test series were calibrated with a Templin calibrator, Fig. 12. It should be noted that the gage factors of the Huggenberger gages was not affected by strain reversal.

Extreme care must be exercised in the use of these gages. Excessive mounting pressure may damage the instrument knife edges. However, sufficient pressure must be applied to prevent slippage of the contact points under action of operational forces. Despite elaborate precautions in mounting, a "lag" usually attributed to slippage is characteristic of the Huggenberger gage. Although the lag may be of little consequence in large strains, serious errors may result in the measurement of small strains such as in the elastic range. Tapping the gage lightly tends to minimize the lag effect. Even considering all the minor disadvantages of the gage, good readings can be obtained if care is taken in mounting and operating it. The Huggenberger gage falls into the A.S.T.M. designation for Class A extensometers which have a maximum error of indicated strain equal to 0.00001 in./in. Extensometers in this class may be used to find the yield stress and modulus of elasticity. The Huggenberger gage is not very good in the plastic and strain hardening ranges, where the strains are very large. Frequent re-setting of the gage indicator is required with the possibility of errors being introduced.

Japanese S-21* electrical resistance strain gages were used on some of the coupons. They have a gage factor of 1.98 and a strain range of about 1 1/2 - 2 percent. The gage length is 5/16" and the width is 5/64". The gage width was 3/64" narrower than the thickness of the CP coupons. Fig. 15 shows an electrical gage mounted on a coupon. AB-5** gages with approximately the same length, width dimensions and a similar strain range were used. The electrical gages proved

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* Distributed by Metrix, Inc., Walnut Creek, California

** Manufactured by Baldwin-Lima-Hamilton, Waltham 54, Mass.

to be very difficult to mount. In the elastic range the gages functioned quite well, however, when the coupon had reached its yield-stress the readings were no longer reliable.

2.4 Compression Jig

The determination of tensile properties of sheet materials has already reached a high degree of standardization. However, no particular method of determining compressive properties in sheet materials has gained acceptance to the extent that standard procedures could be established.

In compression tests of sheet material it is necessary that sufficient lateral support be furnished to prevent premature buckling of the coupon. Without lateral support it is unlikely that certain quantities, such as yield strength, and strain hardening strain could be obtained for thin coupons. While offering support, the jig should not introduce any restraint to lateral expansion of the specimen. The increase of the thickness of the sheet under axial compression is restrained to some extent, however, by certain types of compression jigs through pins, rollers, or guides.

A survey was made of jigs previously designed. A brief description of some of the more important jigs is given in order to acquaint the reader with the different types already used. A discussion of the advantages and disadvantages of these jigs is also given. After considering the merits of the various types, a jig was designed exhibiting most of the desired characteristics.

Most of the methods for making compression tests were devised in the 1940's. One of the earlier methods is the so called "pack method" introduced by Messrs. C. S. Aitchison and L. B. Tuckemen.[3] The pack method obtains lateral support in the weak, thickness direction by means of a sufficient number of pieces of the same material stacked on both sides of one wider coupon on which the strain gages are mounted. The laminations are cemented with shellac. The outside sheets are supported by rods, which are braced by an exterior framework. The whole assemblage is loaded during the test. Probably the most serious disadvantage of the pack method is the high cost of machining the relatively large coupons that must be prepared. Furthermore, pack specimens of thin and strong materials tend to buckle not withstanding the elaborate support. The time required to set up the coupons in the testing machine is rather lengthy because of the large number of steel pins that must be individually adjusted to restrain the coupon laterally during a test.

A cylinder method of testing introduced by Messrs. R. Franks and W. O. Binder requires rolling the sheet material into a tube.[4] The ends of the tube are turned and ground preparatory to end loading during the compression test. Such cylinders are prevented from buckling locally by maintaining a certain maximum diameter-to-thickness ratio. Primary buckling is prevented by maintaining a certain maximum length-to-diameter ratio. The principal objection to the use of the cylinder method is the cold working that the specimen must undergo in forming a satisfactory cylinder. Cold working introduces uncertainties in the mechanical state of the metal. Metals that have already been cold rolled are probably not as seriously affected by the forming of the cylinder. However, annealed, mild or low-alloy steels develop residual stresses when formed into cylinders. Annealing of such cylinders may wipe out residual stresses, but it may change other initial properties.

Thin steel sheaths were used by G. Welter to prevent his aluminum coupons from buckling.[5] The compression load was applied by means of small platens. The main disadvantage of an arrangement such as Welter's is the numerous screw attachments needed for his type of setup. Also a sturdier setup would be needed for steel coupons and thus does not seem to be practical.

W. P. Montgomery and R. L. Templin devised a jig in which support was provided by rows of 0.093 in. rollers spaced 0.10 in. apart.[6] It was argued by others that to supply the lateral support by a series of rollers rather than solid guides did not seem to be the correct procedure, because the rollers might not necessarily turn and because they would have a tendency to indent the coupon.[5] However, it seems to the writer that the rollers would have to turn since the frictional force that would be developed on the coupon would probably be greater than the resisting force developed by the roller on the pin. Test values obtained using this jig compared favorably with values obtained from the "pack" method. Although test values from the jig were good, it was decided that a jig giving similar test results, but easier to fabricate would be used.

A fixture for compressive tests of thin sheet material was designed by J. Miller.[7] It consisted of two hardened steel guides between which the coupon was held by two adjustable clamps. Miller tested aluminum coupons 1/2 in. wide by 2 1/4 in. long. His test results were in good agreement with those obtained by the pack method and the Montgomery-Templin jig.

A jig similar to Miller's was designed by H. LaTour and D. Wolford, for testing steel coupons 1/2 in. wide and 2 in. long.[6] The test results compared favorably with results obtained from coupons tested with the "pack" method and Montgomery-Templin single thickness method. Test values were also compared with values obtained from short unsupported coupons and good correlation was observed. This jig is much easier to fabricate than the others and at the same time it gives reliable test results.

The LaTour-Wolford jig was selected for this project.* A modified version of it was designed and fabricated, Figs. 4 and 13. All portions of the jig were smoothly finished. The edges of the lateral support blocks next to the coupon were machined with a groove in order that the Huggenberger gages could be attached to the coupons without interference from the blocks. The grooves can be seen in Fig. 13. The movable support block was given skew sides in order that support from the whole face of the block could be given to flange specimens which have a variable thickness.

2.5 Bearing Block and Subpress

In compression testing, coupon ends should bear against smooth finished surfaces. These surfaces should be as parallel as possible. It is necessary in compression testing that the load be applied concentric to the coupon. Corrections for errors of nonparallelism of the testing machine

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* Permission was obtained to fabricate the jig from the Armco Steel Corporation who hold the patent rights.

head and bed can be readily made with an adjustable bearing block. Such a bearing block was used in some of the tests. The block is essentially comprised of two hardened steel disks one surface of each being out of parallel with the other by a definite but relatively small amount. The disks are made so that when one is placed upon the other, with the thickest dimension of one opposite the thinnest of the other, the overall thickness of the two will be constant. As one of the tapered disks is rotated upon the other the assembly as a whole becomes a tapered disk.

It was found, however, that the use of a subpress was more advantageous. The subpress corrects automatically for any nonparallelism of the machine head. However, it does not correct for irregularities in the coupon. Pieces of tissue paper were placed between the coupon and subpress when nonparallel coupon ends were indicated during coupon alignment.

3. COMPRESSION COUPONS

The test coupons were cut from plates and stiffeners composing stiffened plate panels of the research program[8]. As it was desired to investigate the material properties at different angles to rolling, coupons were taken at 0°, 45° and 90° to the direction of rolling. The location from which the test coupons were taken is shown in Figs. 2 and 3. Tables 1 and 2 give the specific location of coupons and their oreintation to the direction of rolling.

The coupons were of two different lengths, 2 3/8 in. and 1 1/8 in. ASTM recommends that in order to obtain a representative stress-strain curve the following requirements should be satisfied[9]:

$$G \geqq b$$
$$G \geqq t$$
$$4.5t \geqq L \geqq G + 2b$$

where:

G = gage length
b = width of coupon
L = length of coupon, and
t = thickness of coupon

The above relationships are summarized in Fig. 14.

The flange and web coupons were of such dimensions that the above requirements could not be met for unsupported coupons. They had a thickness of approximately 0.12 in. which would make the required length 0.54 in. or less. This is impractical for testing, also the gage length requirement could not be met. Therefore, it was necessary to fabricate a compression jig. All 1/4 in. thick coupons originating from the plates could be tested without a jig. However, twenty-four plate coupons (Fig. 15) were made of such size so as to make the lateral support necessary. This was done in order that a comparison could be made between supported and unsupported coupons.

The compression jig was made 2.25 in. in height. The supported coupons extended 1/8" beyond the jig, thereby providing sufficient length of coupon when testing into strain hardening was desired.

Coupons were fabricated from original and heat-treated (T-8 and T-9) plate panel material[8]. A comparison was made to determine the effects of heat-treating on compressive properties.

Care was taken to produce no local deformations or cold working effect due to the machining process. The test coupons were sawed from the spare portions of plates and stiffeners, Figs. 2 and 3. They were brought to their final shape by a finish surface grinder in bundles of nine to siz. In all thirty-eight coupons of 2 3/8 in. length and eighteen coupons of 1 1/8 in. length were fabricated. Lengths were measured within 0.001 in. while width and thickness dimensions were measured within 0.0001 in.

4. TEST PROCEDURE

The test procedure can be broken down into four main operations: cleaning the coupon and jig, attaching the strain gages, alignment of the coupon in the subpress, and finally, loading. They are discussed in the order of their occurrence in the testing.

First the coupon ends and the bearing surfaces were cleaned before placing the coupon in the jig. The coupon was given a thin coat of white petroleum jelly and inserted between the lateral supports of the jig. The coating was given to help prevent the development of large frictional forces on the specimen sides. The adjustable screws on the jig were tightened until the specimen barely slid between the support blocks under its own weight. After a little practice approximately the same amount of restraint could be consistently applied. When the sliding of the coupon is not smooth but jerky, there may be foreign matter between the coupon and the supports. The lower end was then centered over the pedestal of the subpress, the excess lubricant having been previously wiped off the bottom of the coupon and jig.

If the coupon was to be tested with electrical strain gages, the gages would have already been attached. However, if the Huggenberger extensometer or Hubermeter was to be used with the coupon, they would be attached at this stage.

Alignment could be checked by applying load and observing the strain increments on both sides of the coupon. Alignment was considered satisfactory if at a stress of 40 percent of the yield stress the strain of any one gage did not deviate by more than ± 5 percent from the average of both gages. If a greater difference then 5 percent was observed, the specimen was shimmed up with thin layers of tissue paper on the shorter side. Alignment could be easily performed with the Huggenberger extensometer or electrical resistance strain gages, but would be inaccurate with the Hubermeter. If the Hubermeter was to be used the Huggenberger extensometers were first attached to align the coupon more accurately.

After alignment was considered satisfactory, load was applied to the coupon. The coupons were loaded, in the elastic range with a cross head speed of .012 in./min.; in the plastic range with a speed of .025 in./min.; and in the strain hardening range with a cross head speed of .012 in./min. Ten to twenty minutes was allowed after each load application for the dynamic effects of the load to fall off. Approximately twelve load and strain readings were taken in the elastic range, with six to eight readings being taken in both the plastic range and the strain hardening range.

5. TEST RESULTS

5.1 General

The compressive properties and other characteristics of the compression coupons are given in Tables 1 and 2. Fig. 15 shows one of the coupons which was tested with an electrical gage. Figs. 16 and 17 show the 1 1/8 in. coupons being tested in the elastic and plastic ranges, respectively. Figs. 18 and 19 show the 2 3/8 in. coupons being tested in the elastic and plastic ranges. Figs. 20 through 23 show tension and compression stress strain curves plotted from average values. All the coupons tested from different sections are represented in these graphs. Figs. 24, 25, and 26 show bar graphs of average values of the static yield stress σ_{sy}, the strain hardening strain ε_{st}, and the strain hardening modulus E_{st} obtained from the tension and compression tests.

5.2 Coupons From Plates of Specimens T1 through T-5

The coupons originating from the plates of specimens T-1 through T-5 were labeled the CP and SP coupons. The CP coupons had a length of 2 3/8 in. while the SP coupons were 1 1/8 in. long. The respective widths were 3/4 in. and 1/4 in.

The CP coupons were tested at 0°, 45°, and 90° to the direction of rolling. The average yield stress obtained in these three respective directions was 41.68, 43.04, and 43.84 ksi. The directional values of the modulus of elasticity were 31.6×10^6, 29.76×10^6, and 31.56×10^6 psi, respectively for 0°, 45°, and 90°. The average values of the yield stress and elastic modulus for all the CP specimens are plotted in Fig. 20 with the corresponding average tension values. It might be noted that the variation from the average yield stress value was a ± 5%, while the variation from the average elastic modulus value was a ± 7%.

A loading and unloading sequence was performed with five of the CP coupons. It gave an average elastic modulus of 31.7×10^6 psi in loading and 30.1×10^6 psi in unloading a difference of 5%. Three of the CP coupons were tested with Huggenberger extensometers; four with S-21 strain gages and two with AB-5 gages.

The SP coupons were tested in two directions to rolling, 0° and 90°. An average yield stress of 43.44 ksi and 44.84 ksi was obtained in the two respective directions. The elastic modulus values in the same two directions were 29.1×10^6 psi and 30.06×10^6 psi, respectively. In determining the average elastic modulus values, the values of 18.5×10^6 psi and 24.6×10^6 psi from coupons SP-1 and SP-3 were not used since the gages had not functioned properly. All SP coupons were tested with Huggenberger gages.

5.3 Coupons From ST3B4.25

The coupons originating from the ST3B4.25 were of two types, flange and web coupons. The coupons were all 2 3/8" long, with 0^o orientation to rolling. An average yield stress of 50.56 ksi was obtained for the web coupons and a 40.30 ksi average for the flange coupons. There was a $\pm$ 5% deviation from the average web yield stress and a $\pm$ 2.5% from the average flange yield stress. The average web and flange elastic moduli were 28.9×10^6 psi and 29.3×10^6 psi, respectively.

A stress strain curve of the average values is shown in Fig. 21. Figs. 25 and 26 show a comparison between tensile and compressive values of ε_{st} and E_{st}. All coupons, except one, which was tested with a Huggenberger gage, were tested with the Hubermeter.

5.4 Coupons From Plates T-6 Through T-10

The coupons designated AP from these plates had similar dimensions as the CP coupons from plates T-1 through T-5. However, some of the coupons in this series were taken from material which was stress relieved by heat treatment. The S and SP coupons also had similar geometric dimensions, however, all S coupons were from stress relieved material.

The coupons which were not stress relieved by heat-treatment exhibited an average yield stress of 43.38 ksi with a $\pm$ 2% variation. The coupons, oriented at 0^o and 90^o to rolling, showed yield stresses of 43.66 ksi and 43.10 ksi, respectively. The average elastic modulus for the coupons was 29.50×10^6 psi. In computing the average values of σ_{sy} and E all coupon test values were included.

The stress relieved AP coupons were all cut at 0^o to rolling. An average yield stress of 40.1 ksi was obtained. In computing the average yield stress the values of coupons AP-9 and AP-14 were excluded. These two yield stress values were 7.2% greater than the average and it was concluded that too much support may have been introduced on these coupons, thus making a load much greater than the true yield stress necessary for yielding.

An average elastic modulus of 29.9×10^6 psi was obtained for the stress relieved coupons. In computing the average elastic modulus the value of 26.7×10^6 psi obtained for AP-1 was excluded. This low value like all the other low elastic moduli previously mentioned were most likely due to the coupon not being in good alignment. Fig. 20 shows stress-strain curves plotted from average values of the data for both types of AP coupons. Figs. 24, 25, and 26 show a bar graph comparison of average test values obtained in tension and compression.

The short 1 1/8" coupons, which were designated the S coupons, showed an average yield stress value of 43.7 ksi. This was 9% higher than the AP coupons which were similarly stress relieved by heat treatment. The higher yield stress values were probably due to the fabrication process. The coupons were brought to their final dimensions with a finish surface grinder which introduced cold working. The influence of the cold working easily affected the whole coupon, since they were of small cross-section. Hence any coupons of small cross-section should be brought to their final dimensions by a process which introduces less cold working.

The average yield stress at 0^{o} and 90^{o} to rolling was 43.5 ksi and 44.3 ksi respectively. The deviation from these values was approximately $\pm$ 2%. The average elastic modulus for all coupons was 29.8×10^{6} psi. Values obtained in the plastic and strain hardening ranges for the S coupons are listed in Table 2.

All AP and S coupons were tested with either a Huggenberger gage or the Hubermeter.

5.5 Coupons From 6Jr4.4

All coupons from this section were at 0^{o} to rolling with four web and four flange coupons tested. Two web and two flange coupons had previously been stress relieved by heat treatment. The regular web coupons showed an average yield stress of 45.9 ksi while the stress relieved web coupons had an average yield stress of 41.6 ksi. The average elastic moduli were 29.25×10^6 psi and 31.7×10^6 psi for the stress relieved coupons.

The average yield stress for flange coupons was 40.05 ksi and 38.05 ksi for the stress relieved coupons. The elastic moduli values were 29.4×10^6 psi and 28×10^6 psi for the stress relieved coupons. Figs. 22 and 23 show stress-strain curves of the average values for the regular and stress relieved coupons. Table 2 gives the individual values of the compressive properties in the plastic and strain hardening ranges for the coupons tested in those ranges.

6. DISCUSSION

The discussion of the results will cover the directional properties of the steel as affected by rolling and heat treatment, a comparison of the compressive and tensile properties, a comparison of values from laterally supported and unsupported coupons, and finally, a discussion of the test equipment specially developed for the tests.

Cold working consists of the plastic deformation of a metal at such temperatures and at such rates that no recrystallization occurs during the process. Under such conditions the metal is strain hardened. The rolling of steel at room temperature is cold working; the rolling of steel at higher temperatures is also cold working provided no recrystallization occurs during the process. Cold working is accompanied by an increase in the yield and ultimate stress and a decrease in ductility.

The yield stress of the CP and SP coupons was greater by 4.9% and 3.9% respectively, in the transverse direction as compared to the longitudinal direction of rolling. However, the AP coupons which were not heat treated had a 1.3% greater yield stress in the direction of rolling than at 90° to rolling. The moduli of elasticity for the coupons were approximately the same in both directions to rolling (0° and 90°). From the data given it can be seen that the compressive properties are dependent on the direction of rolling, however, no consistent relationship could be established. Possibly with a greater number of tests come definite relationship could be determined. Most likely there would be no great difference in the yield strength at different directions to rolling for carbon steel. However, it should not be assumed that this is the case for all steels. Tests have been made by others on austenitic stainless steels, which become quite anisotropic when strengthened by cold rolling.[10] However, tests run on cold rolled low-carbon, mild and high-strength steels showed only slight variations in the stress-strain characteristics with respect to grain direction which was similar to the tests described in this paper. It can also be concluded that cold rolling has little if any effect on the modulus of elasticity of the metal. This has also been found to be the case in tests made by others.[11]

Heat treatment has the effect of changing the properties of the material besides relieving residual stresses. Two separate groups of heat treated coupons, the AP and S, were tested. The heat treated AP coupons showed a yield stress which was 8.2% smaller than similar AP coupons which were not stress relieved. Similarly, the web and flange coupons which were stress relieved showed a yield stress 9.4% and 5.0% lower than similar coupons which were not stress relieved. Hence, it can be concluded that stress relieving by heat treatment does lower the yield stress by approximately 5 to 10%.

The S coupons which were made from the same heat treated plate material as the AP coupons which were heat treated did not show the same low yield stress. The higher yield stress was apparently due to the finish grinding of the fabrication process. The surface cold working due to the grinding easily affected the whole coupon since the cross-section was small. The elastic moduli values of the S and AP coupons, however, were approximately the same.

Before comparing the results from the compression and tension tests, a brief description of the tension coupons and method of testing is presented[8]. The dimensions of the tension coupons were specified according to the ASTM standards (Designation E-8-54T). A gage length of four inches was used, and the width of the reduced section was 3/4 in. The tension tests were conducted with a Tinius Olsen Testing machine of 120,000 lb. capacity (the same machine was used for the compression tests). In each test, an extensometer (Tinius Olsen Type S-1) was first attached to the coupon and a load-strain curve was automatically plotted until the strain hardening curve was well established. Then the extensometer was removed and the strain readings were taken using a pair of dividers and a ruler with one hundredth inch divisions. Average strain rate used was 0.02 in/min before yielding a 0.36 in/min after yielding. The yield property of the material was defined by the static yield stress level, that is the yield stress for a zero strain rate.

All of the compression coupons showed a considerably higher yield stress than the tension coupons. The compression coupons from the plate of T-1 through T-5 showed a yield stress 7.9% higher than the tension coupons, while the web and flange coupons from the ST3B4.25 showed yield stresses 9.0% and 7.5% higher, respectively. The coupons from plates T-6 through T-10 had yield stresses 9.8% and 10.1% higher than the tension coupons for the regular and heat treated coupons, respectively. The greatest difference between the tensile and compressive yield stress values was for the 6Jr4.4. The nonheat treated web and flange coupons showed values 15.6% and 11.5% higher than similar tensile coupons while the heat treated coupons exhibited a yield stress 19.5% and 14.6% higher for the web and flange coupons, respectively. The web and flanges had skewed sides, thus it may be that the lateral support was too great on certain portions thereby giving rise to erroneous results.

Tests made by others also showed higher values for yield stress in compression than in tension. However, none have shown the extreme differences found in the 6Jr4.4. Compression tests run by Johnston and Opila showed a 1.8% higher yield stress in compression than in tension[12]. Their coupons were 3/4 in. thick and did not require a jig. The coupons in this test series were 1/4 in. thick or less. When material is rolled to thinner thicknesses the stress strain characteristics are affected to a greater extent by rolling. Tests conducted by Collins and Dolan on carbon steel, showed yield strength values from 6.5% to 8% higher in compression than tension[13]. Their coupons were cylindrical in form with a length to diameter ratio ranging up to six.

It has been noted by others that cold working tends to produce a gradually rounded stress-strain curve with a higher yield stress in compression than in tension very likely[11].

The moduli of elasticity for compression and tension coupons were found to be essentially the same in these tests. This was also found to be the situation in the tests by others.

The values obtained for the strain hardening modulus and strain hardening strain in tension and compression do not show any definite relationship. This can be seen in Fig. 26. The average values in compression are both higher and lower than the tension values.

In compression testing a choice has to be made whether to use supported or unsupported coupons. Each method has its advantages and disadvantages. The short unsupported coupons have a tendency to give high yield stress values due to the smallness of coupons and thus a greater effect of cold working during the fabrication of the coupons. With supported coupons there is the possibility that too much support may be given. If this occurs, the increase in thickness of the coupon under axial load is prevented, thereby lessening the axial shortening under a given load. Hence, there will be an increase in the apparent yield stress, and elastic modulus. This effect would be more serious for thicker coupons[14]. At high stresses or in the plastic range this condition would have a greater effect on the strains measured.

The readings obtained from the Huggenberger gages were generally very good. The low values of the modulus obtained on coupons SP-1 and SP-3 was probably due to the coupons being out of alignment in the thickness direction. Although the readings appeared good, the misalignment could not be detected by two gages. Hence, for perfect alignment four gages should be used with the rectangular coupons. The erroneous values were from the short 1 1/8 in. coupons which were very difficult to align.

Strain readings obtained from the SR-4 gages gave elastic moduli values of 31×10^{6} psi which were rather high when compared with values obtained from mechanical gages. However, the compressive elastic moduli obtained with the mechanical gages were approximately the same as the elastic moduli obtained in tension. This would seem to indicate that the elastic modulus in compression is best obtained with Huggenberger or other mechanical gages.

The Hubermeter was designed primarily for measuring strains in the plastic and strain hardening range. The gage was used in the elastic range but the readings were not very accurate. An especially wide scatter of points was observed in the early part of most of the elastic stress-strain curves. Thus, the curves plotted with Hubermeter readings were not as good as the curves plotted from the Huggenberger extensometer readings. It was thus found expedient to use Huggenberger gages in the elastic range and then switch to the Hubermeter in the plastic and strain hardening ranges.

7. SUMMARY

This section summarizes the results obtained from the compression tests. Any observed property of the material is stated. Recommendations on the testing procedure are made. Advantages of the various testing equipment are mentioned.

1. The heat treated coupons tested showed approximately 8.5% lower yield strengths than the nonheat treated coupons in both tension and compression.

2. Compression coupons showed 8 to 10% higher yield stresses than the tension coupons.

3. The elastic modulus of steel was approximately the same in tension and compression.

4. The yield stress was dependent on the direction of rolling, however, no consistent correlation could be established.

5. The strain hardening strain and strain hardening modulus obtained in compression had the same magnitude and scatter as the values obtained from the tension tests.

6. The final shaping of the short compression coupons was performed with a finish surface grinder. This process introduced cold working which affected the yield stress. Hence, a fabrication process introducing less cold working should be used on coupons of small cross-section.

7. In compression testing all strain and load readings should be taken at zero strain rate. If a valid comparison is to be made between tensile and compressive values this should also be done in the tension tests.

8. The Huggenberger gage proved to be the most accurate of the gages in the elastic range, although it was also the most tedious to use. Four Huggenberger gages should be used if possible on the short rectangular coupons for determining elastic moduli. The short coupons are hard to align and four gages would make the alignment easier to perform. The Huggenberger gage gives poor readings in the plastic and strain hardening ranges where large strains occur since the gage is very sensitive and frequent resetting is necessary.

9. Judging by the rather high values obtained in these tests SR-4 gages should not be used in determining elastic modulus values. Other disadvantages of the SR-4 gages are the time and care needed for cementing them and their cost.

10. The Hubermeter proved to be an excellent gage for the plastic and strain hardening ranges. It should not be used in the elastic range, however, since it cannot accurately measure the small strains of this region.

8. NOMENCLATURE

σ_{sy} The yield stress at zero strain rate: "static" yield stress.

σ_y The yield stress level is the average stress during actual yielding in the plastic range.

ε_{st} The strain at the onset of strain hardening.

E_{st} The ratio of stress to strain in the strain hardening range.

9. TABLES AND FIGURES

248.10

Table 1a. COMPRESSION COUPON TEST RESULTS (T-1 to T-5)

Coupon	Length in.	Area in.^{2}	Avg. thickness in.	σ_y ksi	E (10^3 ksi)	E_{st} (10^3 ksi)	ε_{st} (in./in.)
1	2	3	4	5	6	7	8
CP-1	2.375	0.1943	0.2589	44.41	30.53		
CP-2	2.374	0.1944	0.2590	42.02	31.41		
CP-3	2.376	0.1927	0.2567	42.68	32.86		
CP-4	2.376	0.1929	0.2568	41.05	28.77		
CP-5	2.376	0.1931	0.2573	41.74	29.77		
CP-6	2.376	0.1935	0.2581	42.27	30.76		
CP-7	2.376	0.1920	0.2559	44.94	31.77		
CP-8	2.375	0.1934	0.2579	43.35	31.02		
CP-9	2.376	0.1919	0.2559	43.25	31.90		
SP-1	1.1245	0.0645	0.2491	43.41	18.50*		
SP-2	1.1295	0.0643	0.2490	44.47	29.90		
SP-3	1.1300	0.0645	0.2491	42.32	24.6 *		
SP-4	1.1260	0.0638	0.2490	44.45	30.15		
SP-5	1.1255	0.0640	0.2492	45.62	30.15		
SP-6	1.1310	0.0636	0.2491	44.60	29.10		
W-I	2.375	0.1210	0.1610	47.50	28.50		
W-II	2.374	0.1228	0.1636	51.20	29.30	0.465	0.0180
W-III	2.374	0.1290	0.1601	53.00	28.90	0.389	0.0229
F-I	2.376	0.1501	0.2001	40.00	31.20	0.370	0.0229
F-II	2.375	0.1465	0.1954	39.50	27.0	0.443	0.0229
F-III	2.377	0.1492	0.1989	41.40	29.8	0.550	0.0180

* Not used in computing average values

Table 1b. COMPRESSION COUPON TEST RESULTS (T-1 to T-5)

Coupon	Orientation to rolling (degrees)	Origin	Gage	Stress relieving
1	2	3	4	5
CP-1	45	T-4	S-21	None
CP-2	45	T-2	S-21	"
CP-3	45	T-3	S-21	"
CP-4	0	T-1	Huggenberger	"
CP-5	0	T-5	"	"
CP-6	0	T-4	"	"
CP-7	90	T-3	S-21	"
CP-8	90	T-5	AB-5	"
CP-9	90	T-2	AB-5	"
SP-1	0	T-4	Huggenberger	"
SP-2	90	T-4	"	"
SP-3	0	T-4	"	"
SP-4	90	T-2	"	"
SP-5	90	T-2	"	"
SP-6	0	T-2	"	"
W-I	0	ST3B4.25	Huggenberger	"
W-II	0	"	Hubermeter	"
W-III	0	"	"	"
F-I	0	"	"	"
F-II	0	"	"	"
F-III	0	"	"	"

Table 2a. COMPRESSION COUPON TEST RESULTS (T-6 to T-10)

Coupon	Length in.	Area in.^{2}	Avg. thickness in.	σ_{sy} ksi	E (10^3ksi)	E_{st} (10^3ksi)	ε_{st} (in./in.)
1	2	3	4	5	6	7	8
AP-1	2.375	0.1872	0.2499	39.52	26.70*		
AP-2	2.375	0.1872	0.2498	40.70	29.31		
AP-3	2.375	0.1872	0.2498	43.70	28.9	0.814	0.01475
AP-4	2.375	0.1874	0.2502	43.20	28.2	0.621	0.01490
AP-5	2.375	0.1869	0.2498	43.80	29.7	0.504	0.01595
AP-6	2.375	0.1871	0.2499	43.80	29.6	0.464	0.0170
AP-7	2.375	0.1868	0.2495	43.40	30.6	0.466	0.01475
AP-8	2.374	0.1874	0.2501	42.40	30.4	0.509	0.01310
AP-9	2.374	0.1870	0.2498	43.00*	29.3	0.544	0.0135
AP-10	2.375	0.1871	0.2500	40.00	30.4	0.624	0.01475
AP-11	2.374	0.1867	0.2499	39.50	29.7	0.604	0.0166
AP-12	2.374	0.1871	0.2500	40.50	28.0	0.510	0.01585
AP-13	2.374	0.1869	0.2499	40.70	30.2	0.447	0.01490
AP-14	2.375	0.1870	0.2500	43.00*	31.6	0.695	0.01550
AP-15	2.374	0.1871	0.2500	39.80	31.0	0.587	0.01410
W-IV	2.375	0.0850	0.1132	40.20	30.4	0.798	0.0230
W-V	2.375	0.0892	0.1190	43.00	33.0		
W-VI	2.375	0.0851	0.1135	45.8	29.4		
W-VII	2.374	0.0849	0.1130	46.0	29.1		
						0.524	0.0169

* Not used in computing average values

Table 2a. COMPRESSION COUPON TEST RESULTS (T-6 to T-10) (Cont'd)

Coupon	Length in.	Area in.^{2}	Avg. thickness in.	σ_{sy} ksi	E (10^3ksi)	E_{st} (10^3ksi)	ε_{st} (in./in.)
1	2	3	4	5	6	7	8
S-I	1.126	0.0621	0.2494	44.6	32.3	0.682	0.012
S-II	1.125	0.0621	0.2493	43.4	30.5		
S-III	1.126	0.0621	0.2490	45.1	31.3	0.621	0.0085
S-IV	1.125	0.0621	0.2492	44.4	29.3		
S-V	1.126	0.0622	0.2495	42.65	29.3	0.715	0.0115
S-VI	1.125	0.0621	0.2492	44.10	29.5	0.694	0.00755
S-VII	1.126	0.0621	0.2492	43.10	29.7	0.652	0.01145
S-VIII	1.126	0.0622	0.2495	42.8	30.2	0.624	0.0125
S-IX	1.126	0.0622	0.2494	43.8	26.6 *	0.491	0.0114
S-X	1.126	0.0621	0.2494	44.1	28.1	0.785	0.01370
S-XI	1.125	0.0622	0.2494	43.1	28.0	0.605	0.0149
S-X-II	1.126	0.0621	0.2490	43.3	30.9	0.437	0.0140
F-IV	2.376	0.1267	0.1693	37.5	29.0		
F-V	2.373	0.1193	0.1596	38.6	27.0	0.602	0.0180
F-VI	2.374	0.1230	0.1650	39.0	30.0		
F-VII	2.375	0.1250	0.1671	41.1	28.8	0.685	0.0156

* Not used in computing average values

Table 2b. COMPRESSION COUPON TEST RESULTS (T-6 to T-10)

Coupon	Orientation to rolling (degrees)	Origin	Gage	Stress relieving
1	2	3	4	5
AP-1	0	T-8	Huggenberger	heat treatment
AP-2	0	T-8	"	" "
AP-3	90	T-10	Hubermeter	None
AP-4	90	T-10	"	"
AP-5	0	T-10	"	"
AP-6	0	T-10	"	"
AP-7	0	T-7	"	"
AP-8	90	T-7	"	"
AP-9	0	T-8	"	"
AP-10	0	T-8	"	heat treatment
AP-11	0	T-8	"	" "
AP-12	0	T-8	"	" "
AP-13	0	T-9	"	" "
AP-14	0	T-9	"	" "
AP-15	0	T-9	"	" "
W-IV	0	6Jr.4.4	"	" "
W-V	0	"	Huggenberger	" "
W-VI	0	"	"	None
W-VII	0	"	Hubermeter	"

Table 2b. COMPRESSION COUPON TEST RESULTS (T-6 to T-10) (Cont'd)

Coupon	Orientation to rolling (degrees)	Origin	Gage	Stress relieving
1	2	3	4	5
S-I	90	T-9	Huggenberger	heat treatment
S-II	90	"	"	" "
S-III	90	"	Hubermeter	" "
S-IV	0	"	Huggenberger	" "
S-V	0	"	Hubermeter	" "
S-VI	0	"	"	" "
S-VII	0	"	"	" "
S-VIII	0	"	"	" "
S-IX	0	"	"	" "
S-X	0	T-8	"	" "
S-XI	0	"	"	" "
S-XII	0	"	"	" "
F-IV	0	6Jr.4.4	Huggenberger	" "
F-V	0	"	Hubermeter	" "
F-VI	0	"	Huggenberger	None
F-VII	0	"	"	"

Table 3. TENSION COUPON TEST RESULTS (T-1 to T-5)

Coupons: Taken from	Coupons: Designation	σ_{sy} (ksi)	σ_u (ksi)	E (10^3 ksi)	E_{st} (10^3 ksi)	ε_{st} (in./in.)	% Elongation	% Reduct. of Area
1	2	3	4	5	6	7	8	9
Plate	Pc-1	39.8	60.2	30.7	-	-	31.3	61.6
	Pc-2	38.8	59.9	27.9	0.701	0.022	30.3	61.3
	Pc-3	-	58.4	28.2	-	-	28.0	60.4
	Pc-4	39.6	59.3	28.9	0.542	0.030	33.1	59.2
	Pc-5	39.4	60.4	30.0	-	-	30.0	58.5
	Pc-6	40.8	60.1	28.9	0.555	0.015	33.0	60.8
	Pc-7	39.8	59.4	29.4	0.630	0.018	33.4	62.4
	Average	39.7	59.7	29.1	0.607	0.021	31.3	60.6
Stiffener Flange	Fc-1	39.2	59.5	36.2*	-	-	31.3	58.7
	Fc-2	36.4	56.9	30.5	-	-	28.3	58.9
	Fc-3	36.3	56.9	31.1	-	-	31.8	58.6
	Fc-4	37.3	58.7	31.3	0.828	0.016	30.1	61.2
	Fc-5	38.4	59.4	30.7	0.689	0.017	29.7	63.0
	Average	37.5	58.3	30.9	0.759	0.017	30.2	60.1
Stiffener Web	Wc-1	47.0	63.7	29.2	-	-	22.8	54.3
	Wc-2	45.5	63.4	31.2	0.590	0.020	23.8	51.6
	Wc-3	46.6	63.1	30.7	0.600	0.022	22.5	51.6
	Average	46.4	63.4	30.4	0.595	0.021	23.0	52.5
Weighted Average		40.0	59.9	29.6	0.632	0.020	30.2	59.6

* This value was not used in obtaining the average E

Table 4. TENSION COUPON TEST RESULTS (T-6 to T-10)

Coupons Taken From	Coupon Number	σ_{sy} (ksi)	σ_u (ksi)	E (10^3ksi)	E_{st} (10^3ksi)	ε_{st} (in./in.)	% Elongation	% Reduct. of Area
1	2	3	4	5	6	7	8	9
	As Delivered							
Plate	Pc-8	40.8	61.3	34.2*	0.522	0.007	21.1*	54.7
	Pc-9	41.4	62.3	31.6	0.539	0.007	32.2	56.1
	Pc-10	40.3	60.7	31.0	0.408	0.007	31.8	59.4
	Pc-11	37.8	59.2	29.2	0.510	0.013	31.3	57.4
	Pc-12	42.0	62.3	29.8	0.655	0.014	28.8	57.4
	Pc-16	37.8	59.5	28.8	0.775	0.011	30.4	53.2
	Pc-17	38.0	60.5	29.6	0.493	0.011	29.8	59.5
	Pc-18	37.9	59.8	29.5	0.650	0.012	31.2	57.2
	Average	39.5	60.7	29.9	0.569	0.010	30.8	56.9
	Annealed							
Plate	Pc-13	35.9	59.4	29.5	0.561	0.022	33.4	55.7
	Pc-14	36.5	60.0	31.7	0.356	0.021	31.4	53.2
	Pc-15	36.8	59.9	33.0	0.507	0.023	32.2	60.0
	Average	36.4	59.8	31.4	0.475	0.021	32.3	56.3
	As Delivered							
Stiffener Flange	Fc-6	32.8	54.1	30.1	0.555	0.021	31.0	56.0
	Fc-7	35.2	58.6	28.1	0.655	0.017	26.9	41.8*
	Fc-8	36.8	58.7	32.2	0.489	0.021	23.5	57.4
	Fc-10	38.2	62.4	29.9	0.769	0.021	25.6	54.6
	Fc-12	36.7	58.6	29.8	0.718	0.016	24.8	47.0
	Average	35.9	58.5	30.0	0.637	0.019	26.4	53.8

Table 4. TENSION COUPON TEST RESULTS (T-6 to T-10)

Coupons Taken From	Coupon Number	σ_{sy} (ksi)	σ_u (ksi)	E (10^3ksi)	E_{st} (10^3ksi)	ε_{st} (in./in.)	% Elongation	% Reduct. of Area
1	2	3	4	5	6	7	8	9
Annealed								
Stiffener Flange	Fc-9	31.7	48.0	33.6	0.449	0.022	30.5	59.3
	Fc-11	34.7	49.3	33.1	0.615	0.019	27.4	-
	Average	33.2	48.6	33.4	0.532	0.020	29.0	59.3
As Delivered								
Stiffener Web	Wc-4	40.9	67.0	34.6	0.481	0.017	25.5	46.9
	Wc-5	38.6	62.4	29.4	0.356	0.021	33.2	50.1
	Wc-6	40.1	60.0	28.8	0.592	0.029	28.8	45.5
	Wc-8	42.0	64.2	32.2	0.574	0.030	29.6	53.6
	Wc-9	36.8	60.0	-	-	-	30.8	60.5
	Wc-10	59.7	59.9	29.1	0.465	0.026	33.7	57.0
	Average	39.7	62.2	30.8	0.494	0.025	30.3	52.3
Annealed								
Stiffener Web	Wc-7	34.8	54.7	30.4	0.731	0.029	29.0	-

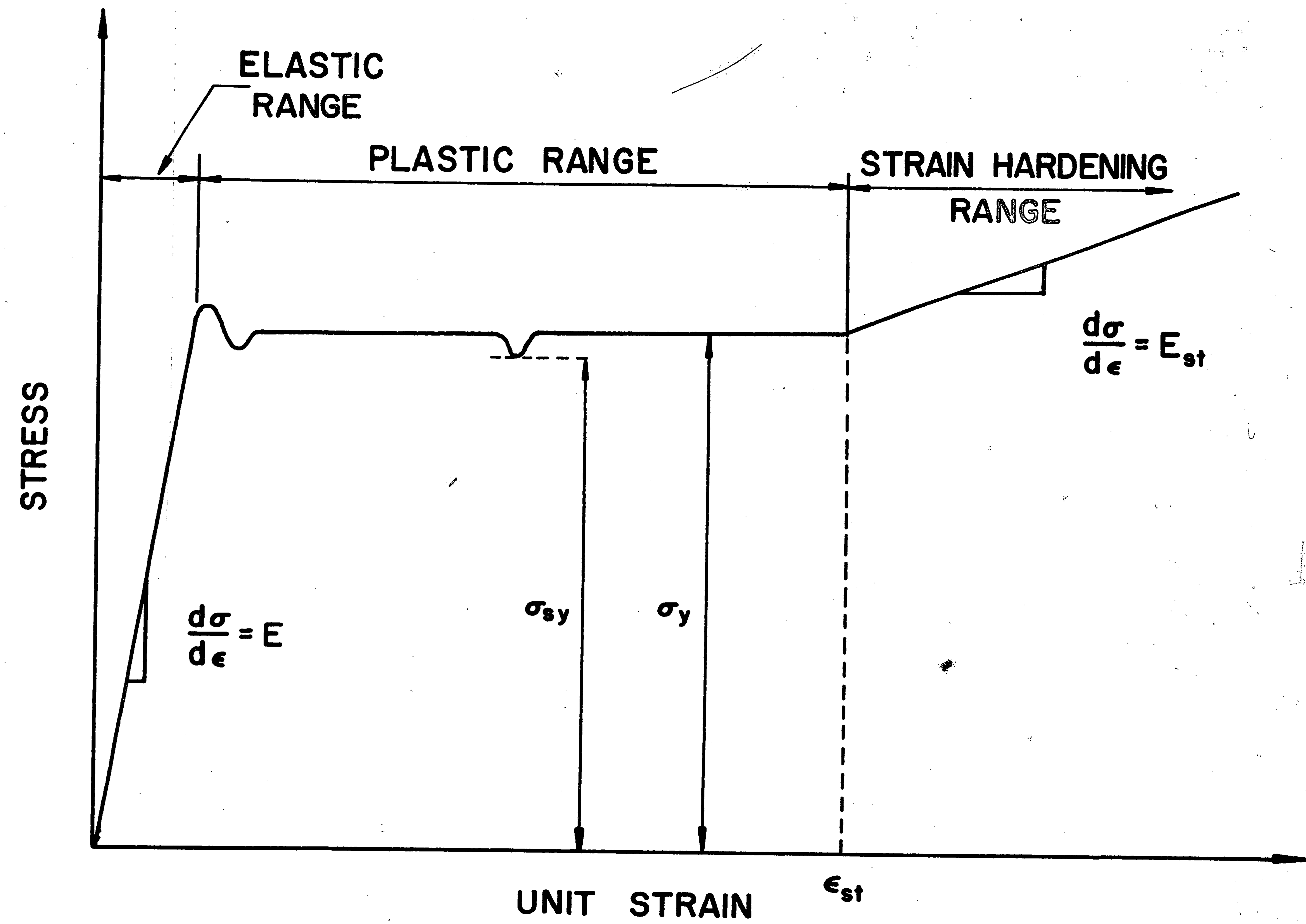
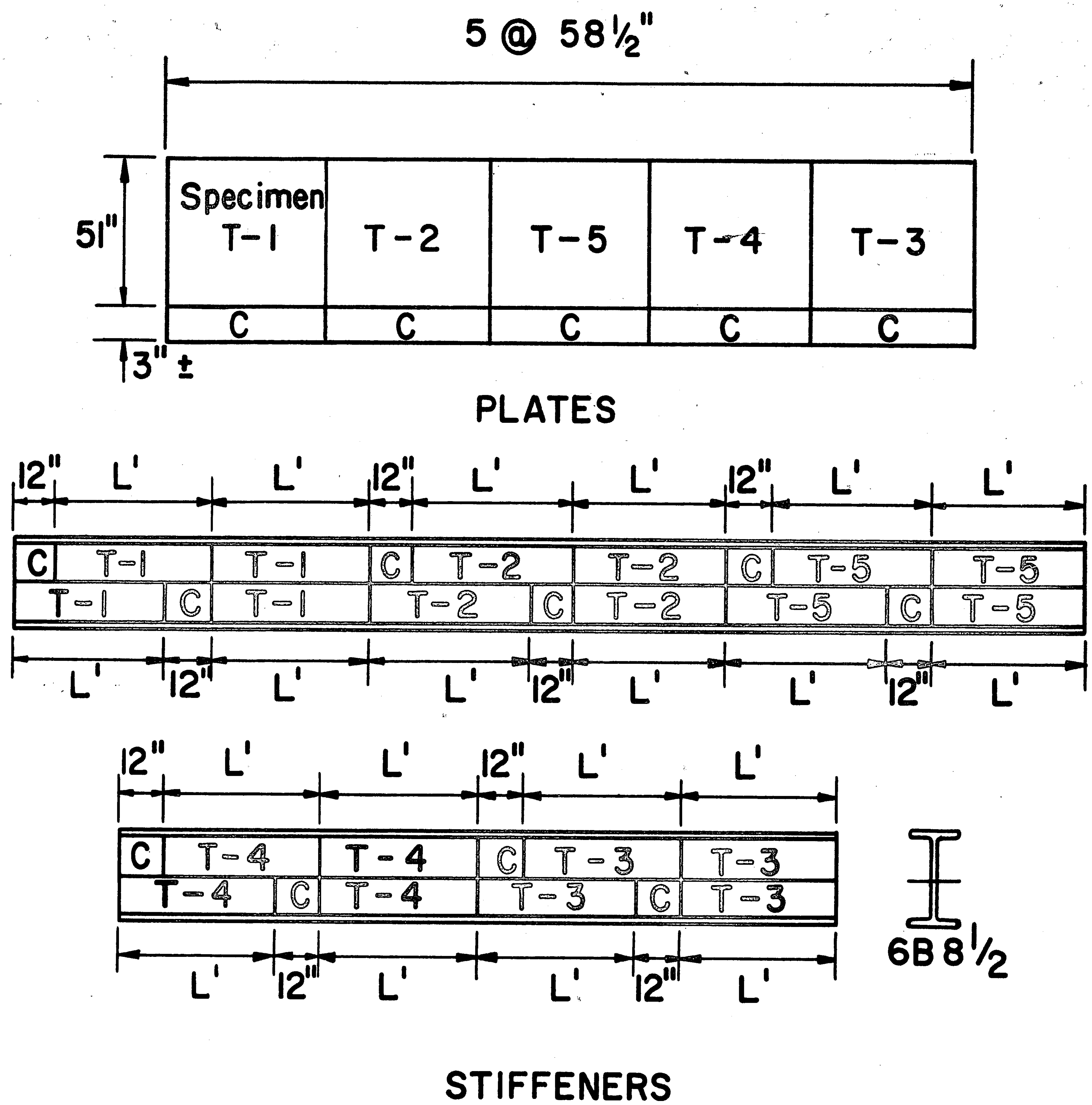


FIG. 1 STRESS-STRAIN CURVE GRAPHICAL DEFINITION OF TERMS



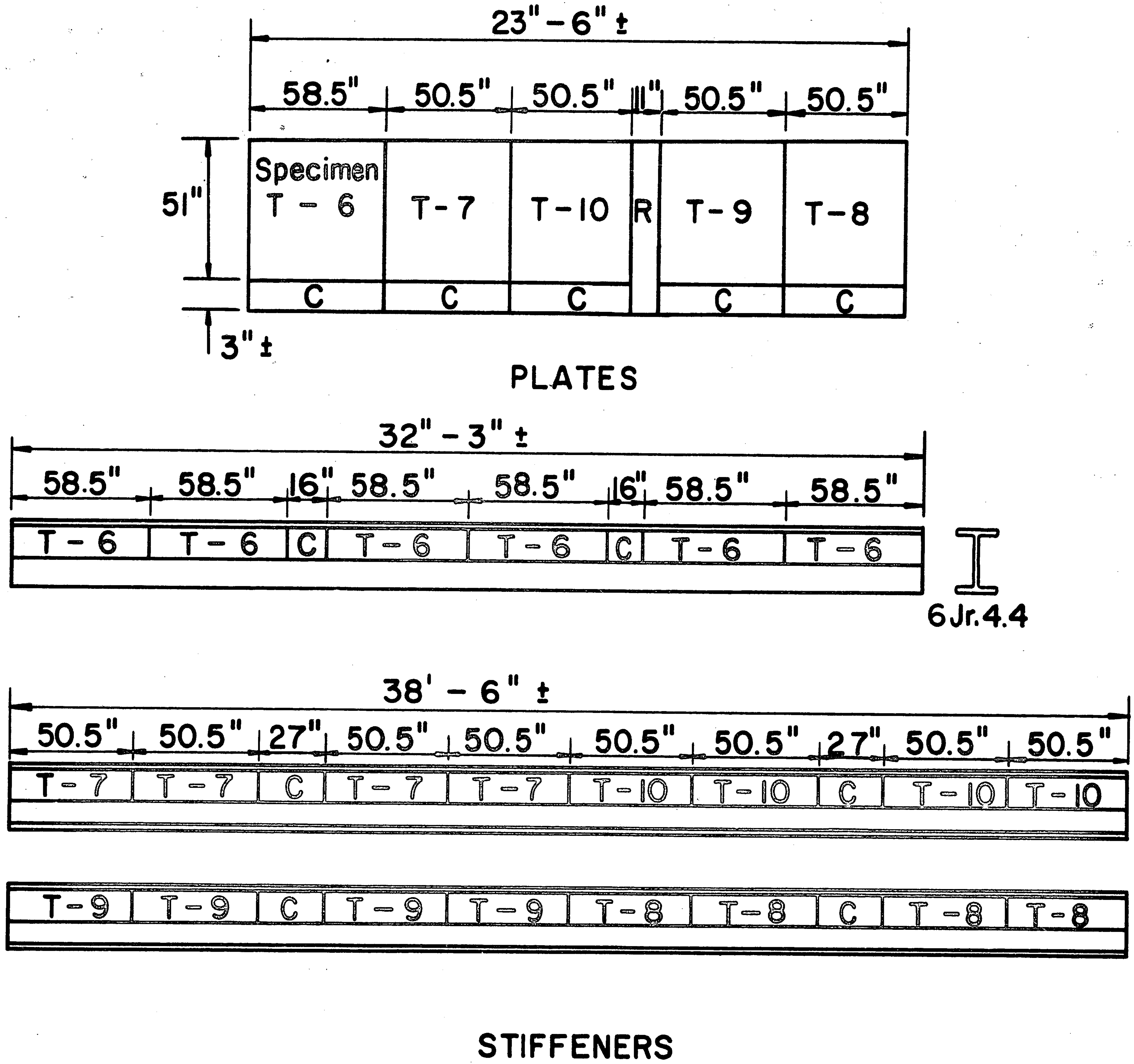
NOTES:

L' : LENGTH OF PANEL = 58½ inches

C : RESERVE PIECES FOR TENSION AND COMPRESSION COUPONS

NO SCALE

FIG. 2 SPECIMENS T-1 THROUGH T-5 PLUS ST3B4.25



NOTE:
C: RESERVED PIECES FOR TENSION AND COMPRESSION COUPONS

NO SCALE

FIG. 3 SPECIMENS T-6 THROUGH T-10 PLUS 6 Jr. 4.4

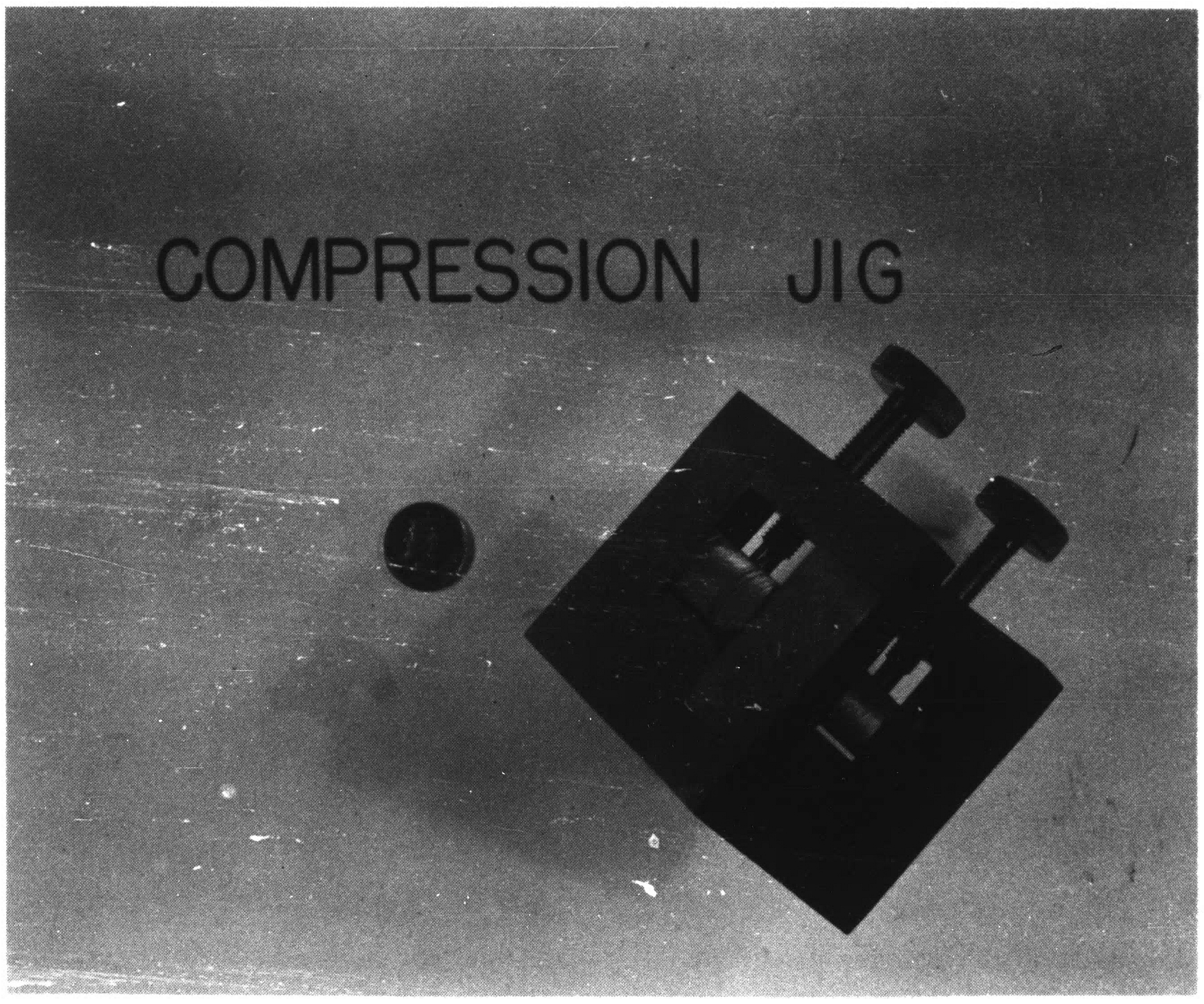


FIG.4 COMPRESSION JIG

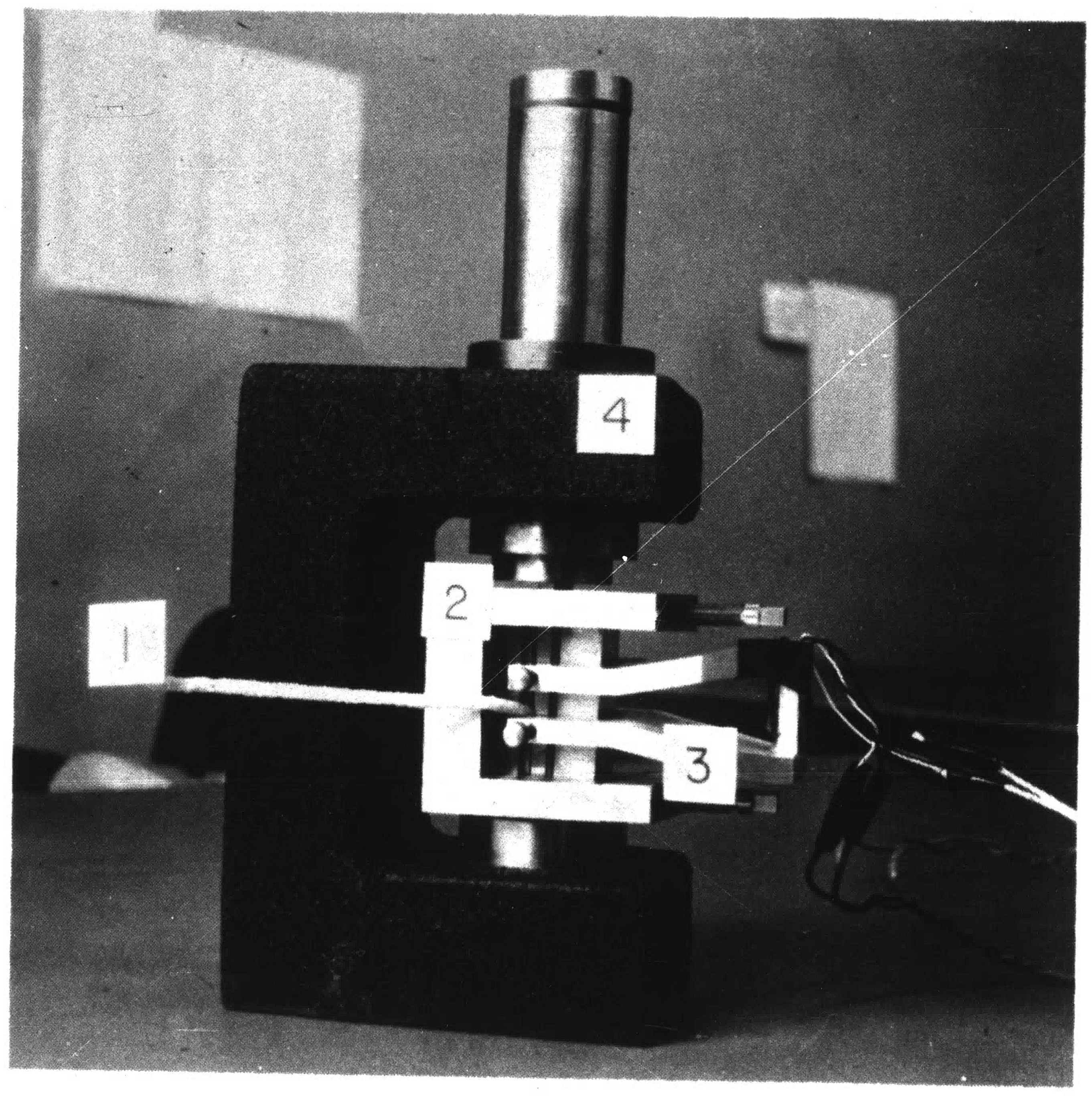
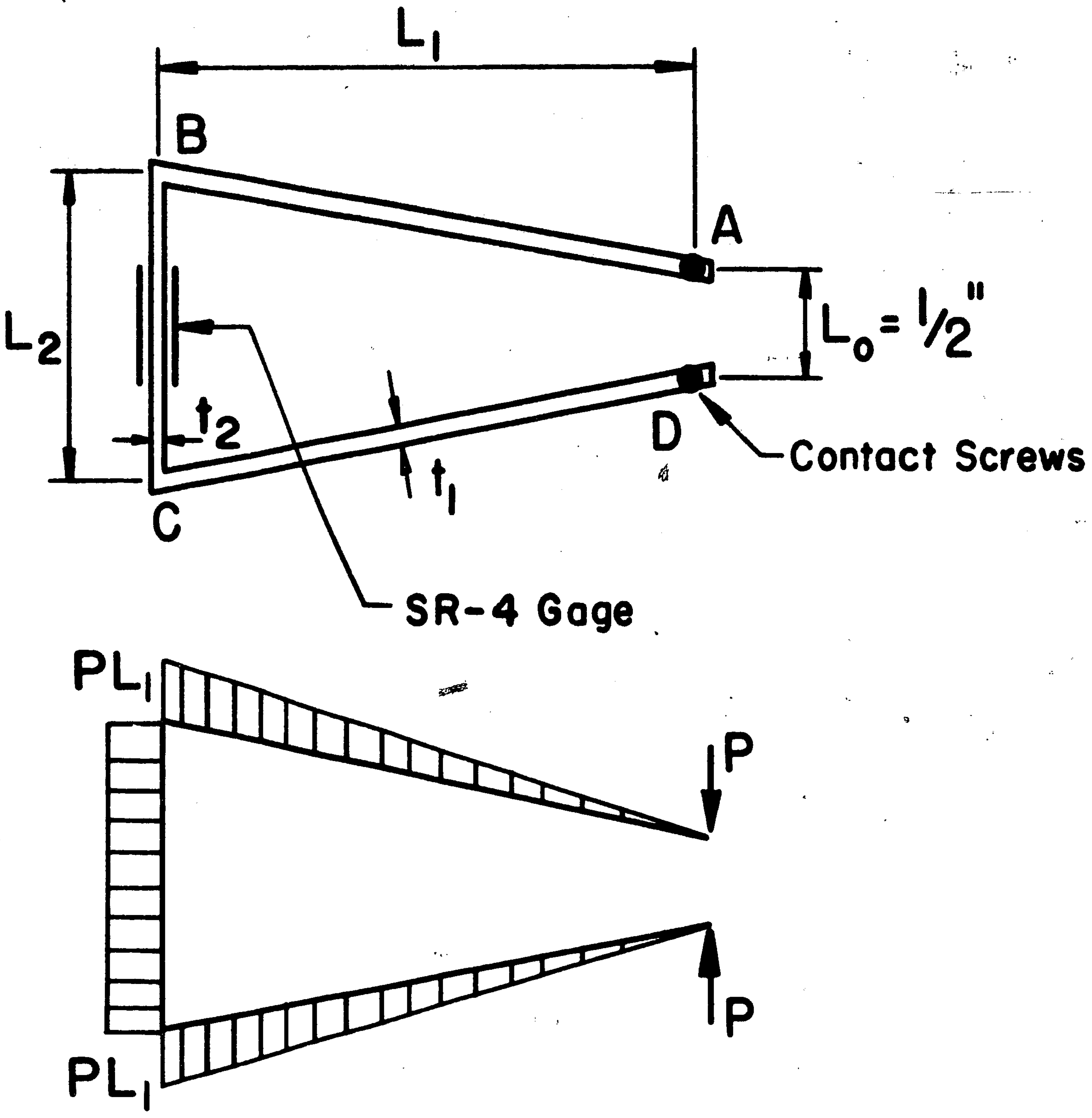


FIG. 5 TEST EQUIPMENT AND COUPON

1. COUPON
2. COMPRESSION JIG
3. HUBERMETER
4. SUBPRESS



Subscript 1 for members AB & CD

Subscript 2 for member BC

ϵ = coupon strain

$\Delta L_o = L_o \epsilon$

E_A = elastic modulus of aluminum

ϵ^* = sum of absolute bending strains

α = gage factor

$$\text{a)}\quad 1 \cdot \Delta L_o = \int_0^s \frac{M_o M_1 d_s}{EI} = \frac{2PL_1^3}{3E_A I_1} + \frac{PL_2 L_1^2}{E_A I_2}$$

$$\text{b)}\quad \epsilon^* = \frac{M_c}{EI_2} = \frac{PL_1 t_2}{E_A I_2}$$

$$\text{c)}\quad PL_1 = \frac{\Delta L_o}{\dfrac{2L_1^2}{3E_A I_1} + \dfrac{L_2 L_1}{E_A I_2}}$$

$$\text{d)}\quad \alpha = \epsilon / \epsilon^* = \frac{L_1 I_2}{L_o t_2}\left[\frac{2L_1}{3I_1} + \frac{L_2}{I_2}\right]$$

The gage factor α is obtained by connecting one SR-4 gage as the active and the other as the dummy gage. Temperature changes have a negligible effect on strain readings; for example a 10° F temperature change gave an $\epsilon^* = 0.000006$ on the Hubermeter designed.

FIG. 6 HUBERMETER DESIGN EQUATIONS

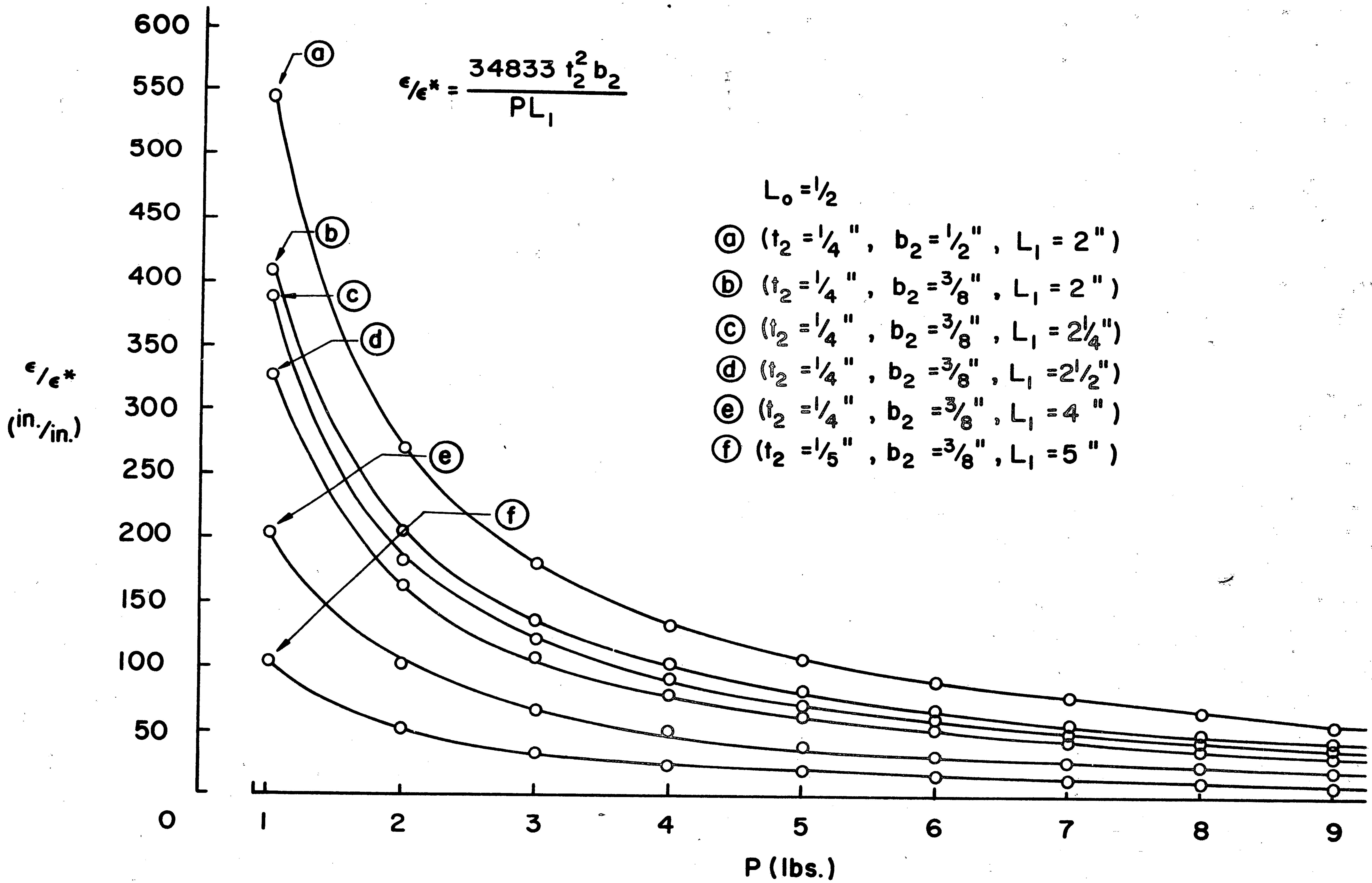


FIG. 7 DESIGN GRAPH II FOR HUBERMETER

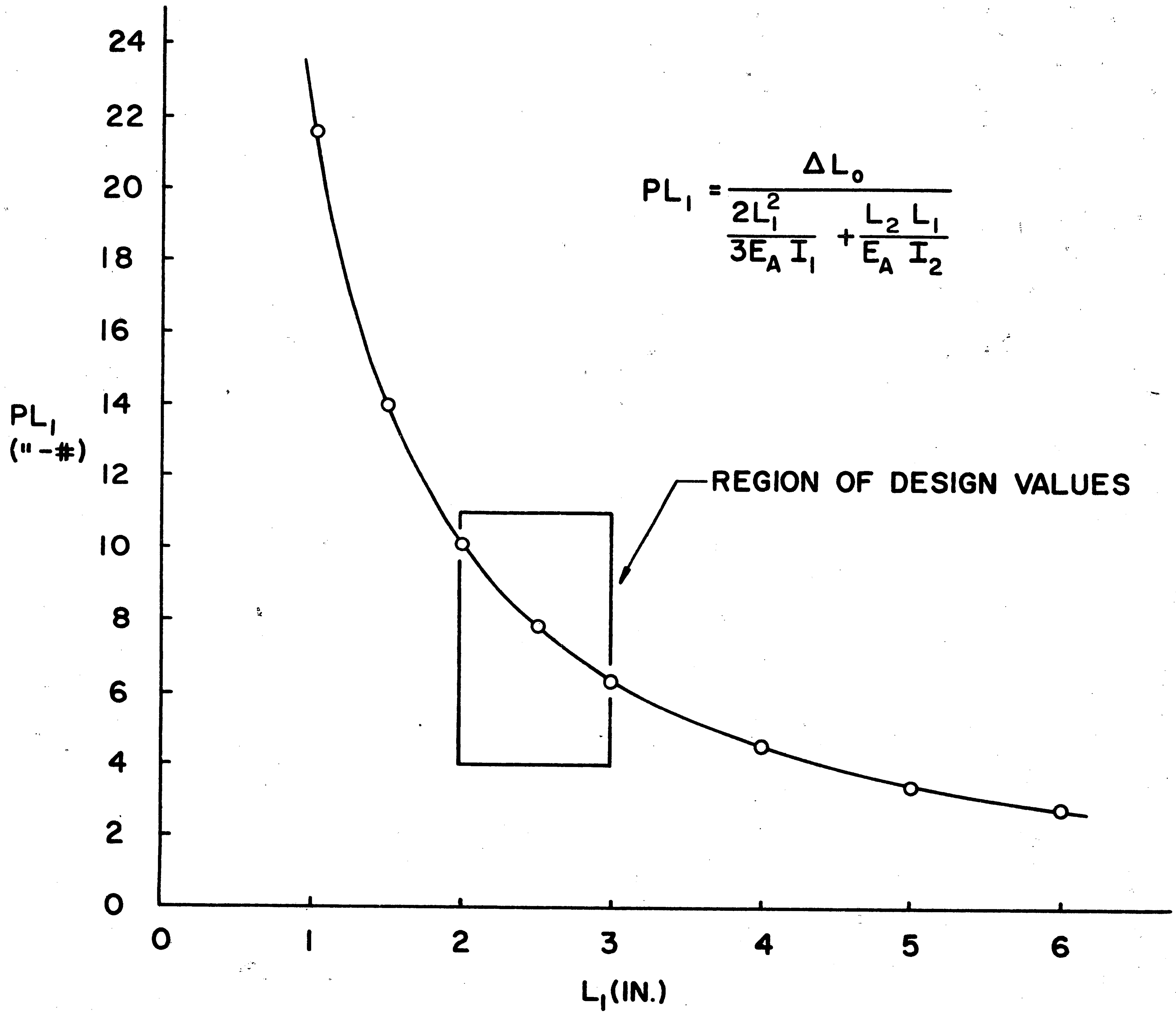


FIG. 8 DESIGN GRAPH I FOR HUBERMETER

FIG. 9 HUBERMETER

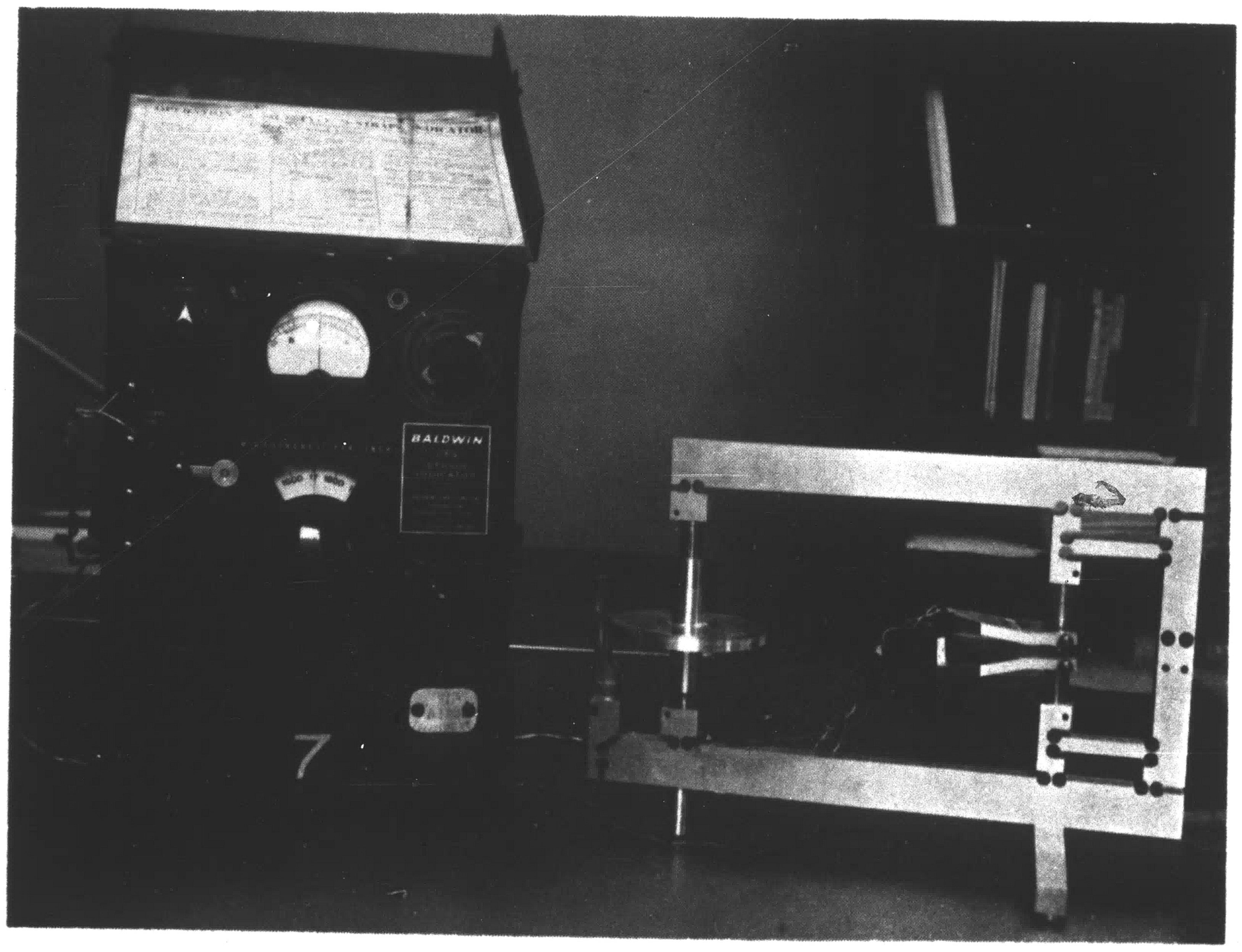


FIG. 10 HUBERMETER CALIBRATION

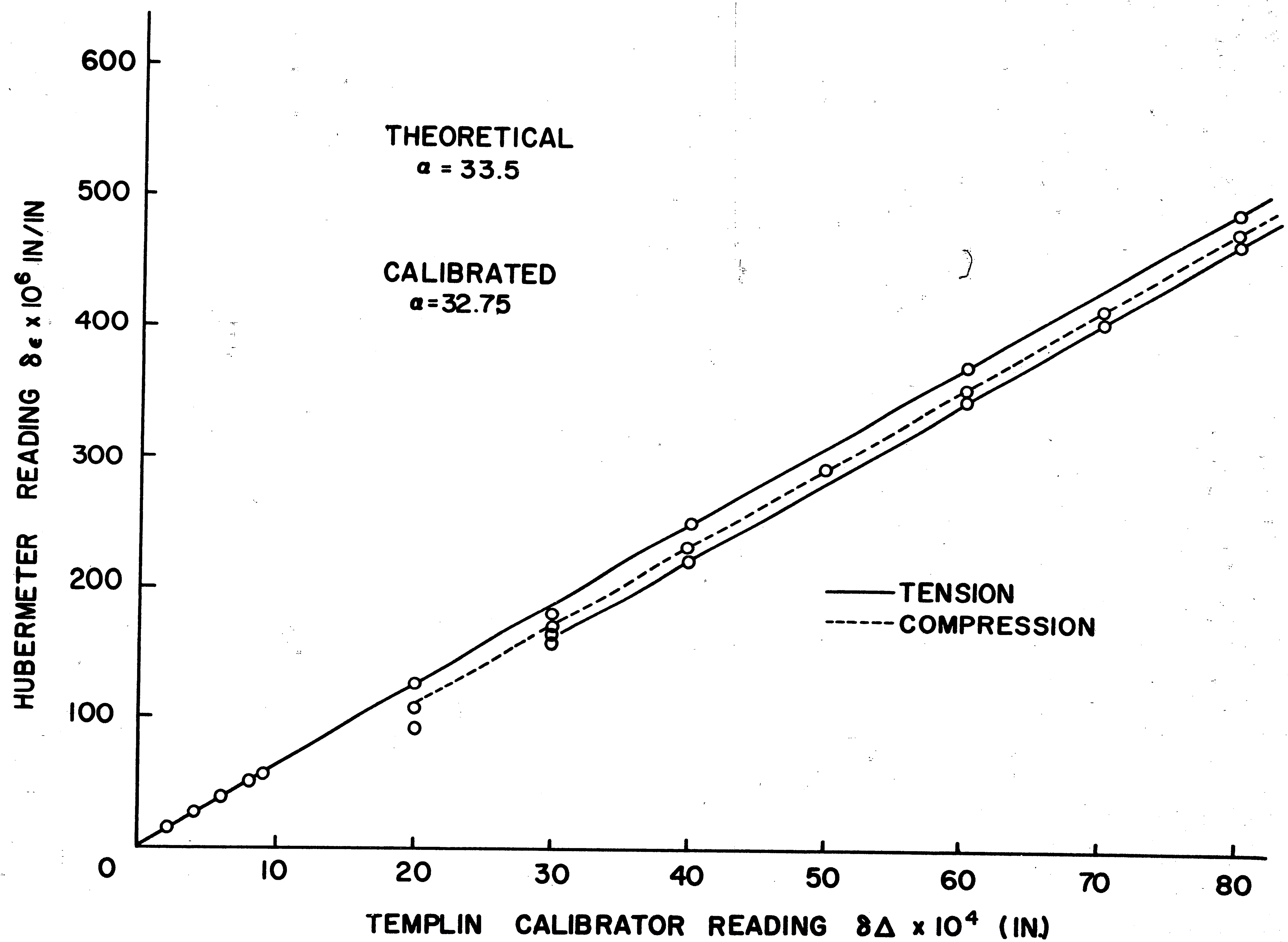


FIG. 11 HUBERMETER CALIBRATION GRAPH

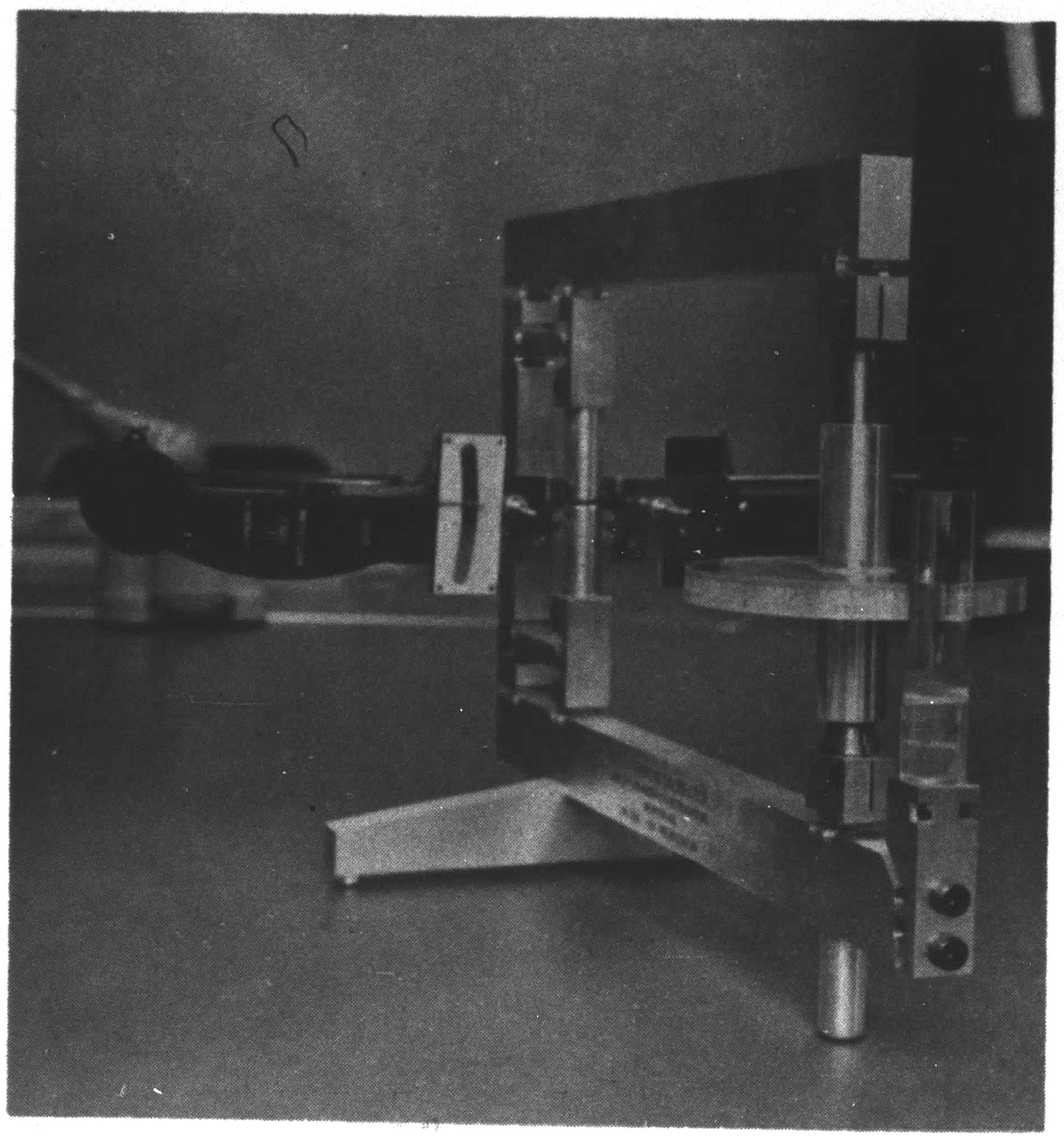


FIG.12 HUGGENBERGER EXTENSOMETER CALIBRATION

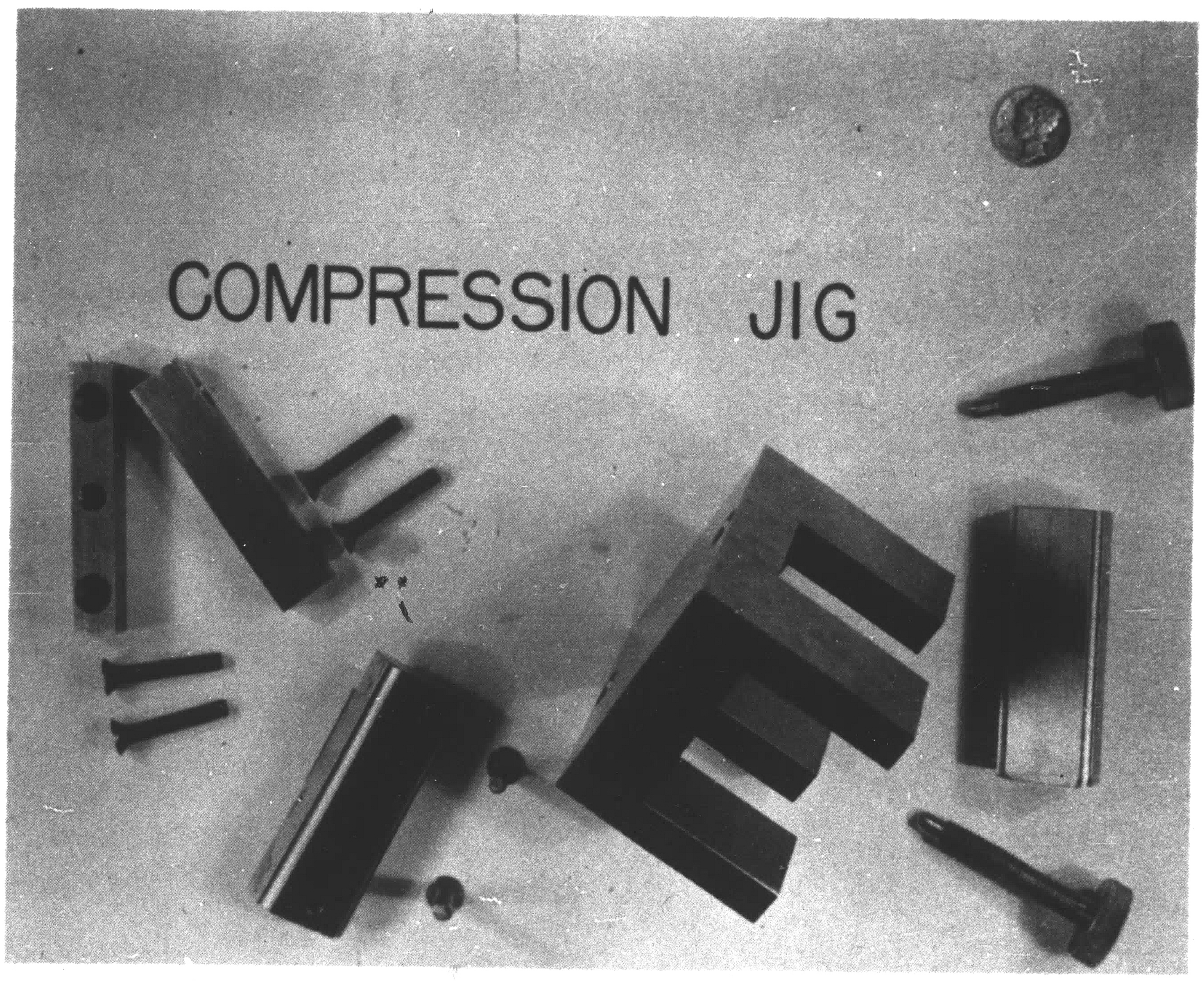
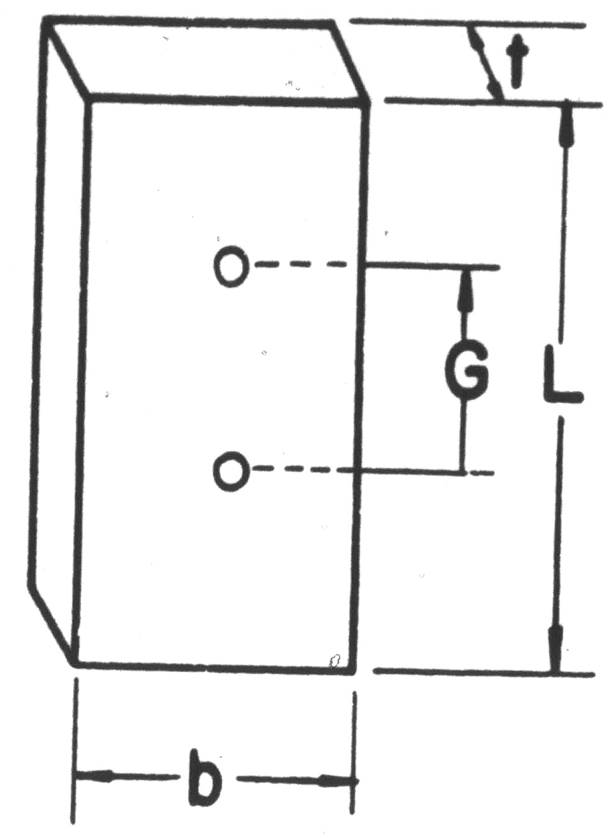


FIG.13 COMPRESSION JIG



$G \geqq t$

$G \geqq b$

$4.5t \geqq L \geqq G + 2b$

G = gage length

b = width of coupon

L = length of coupon

t thickness of coupon

FIG. 14 UNSUPPORTED COUPON DIMENSION REQUIREMENTS

FIG. 15 TEST COUPON

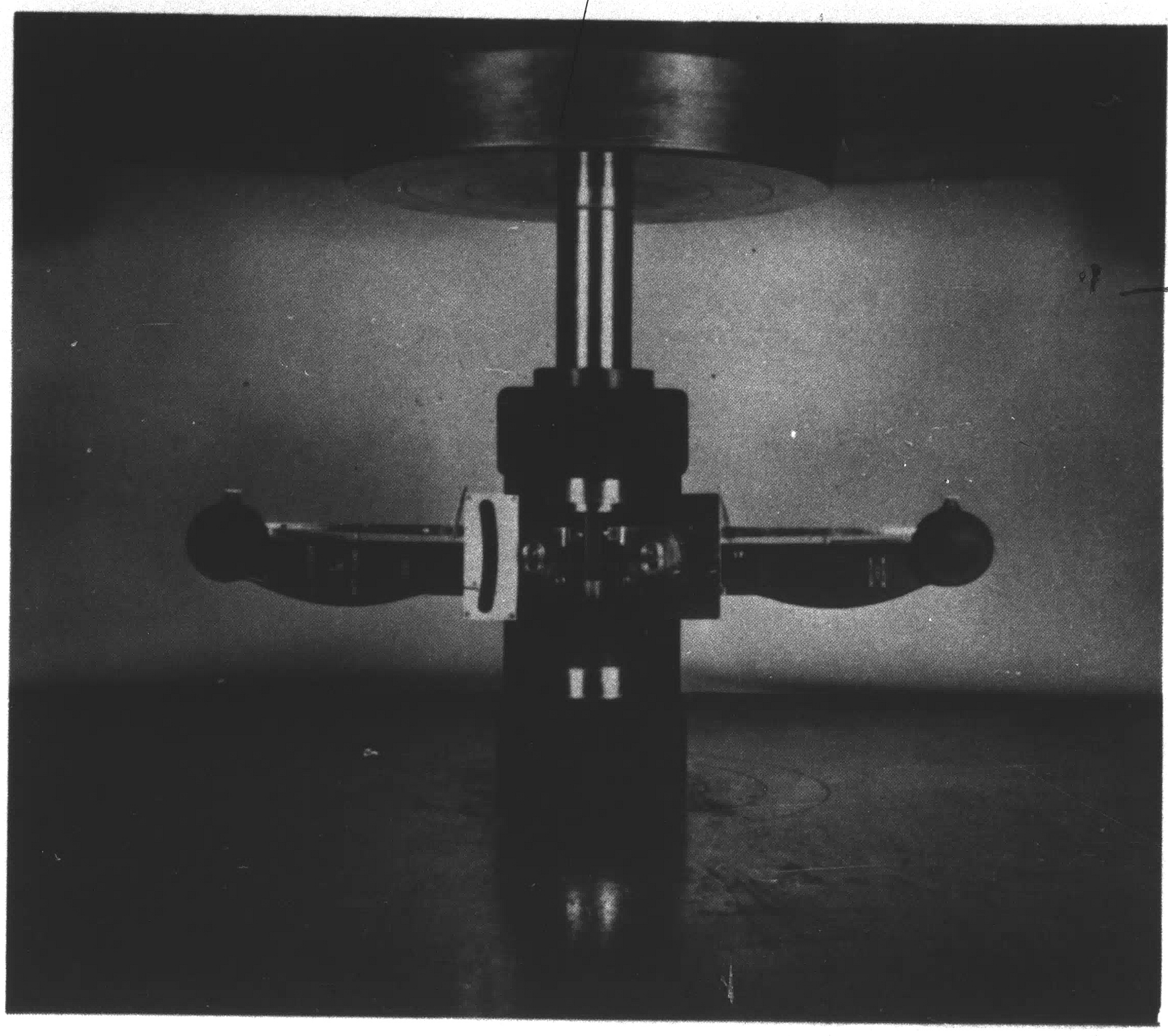


FIG. 16 TEST SET-UP FOR 1⅛" COUPON

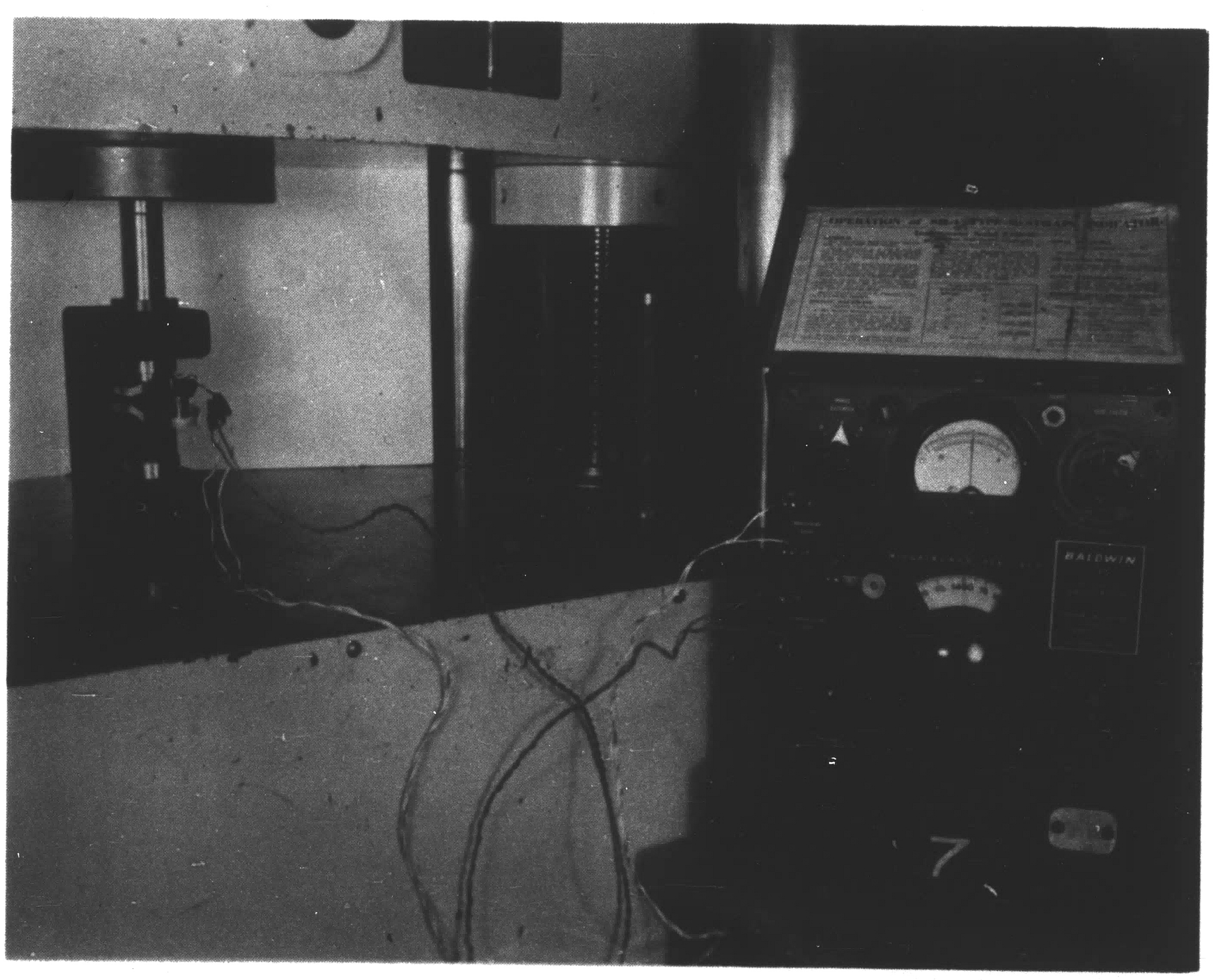


FIG. 17 TEST SET-UP FOR 1⅛" COUPON

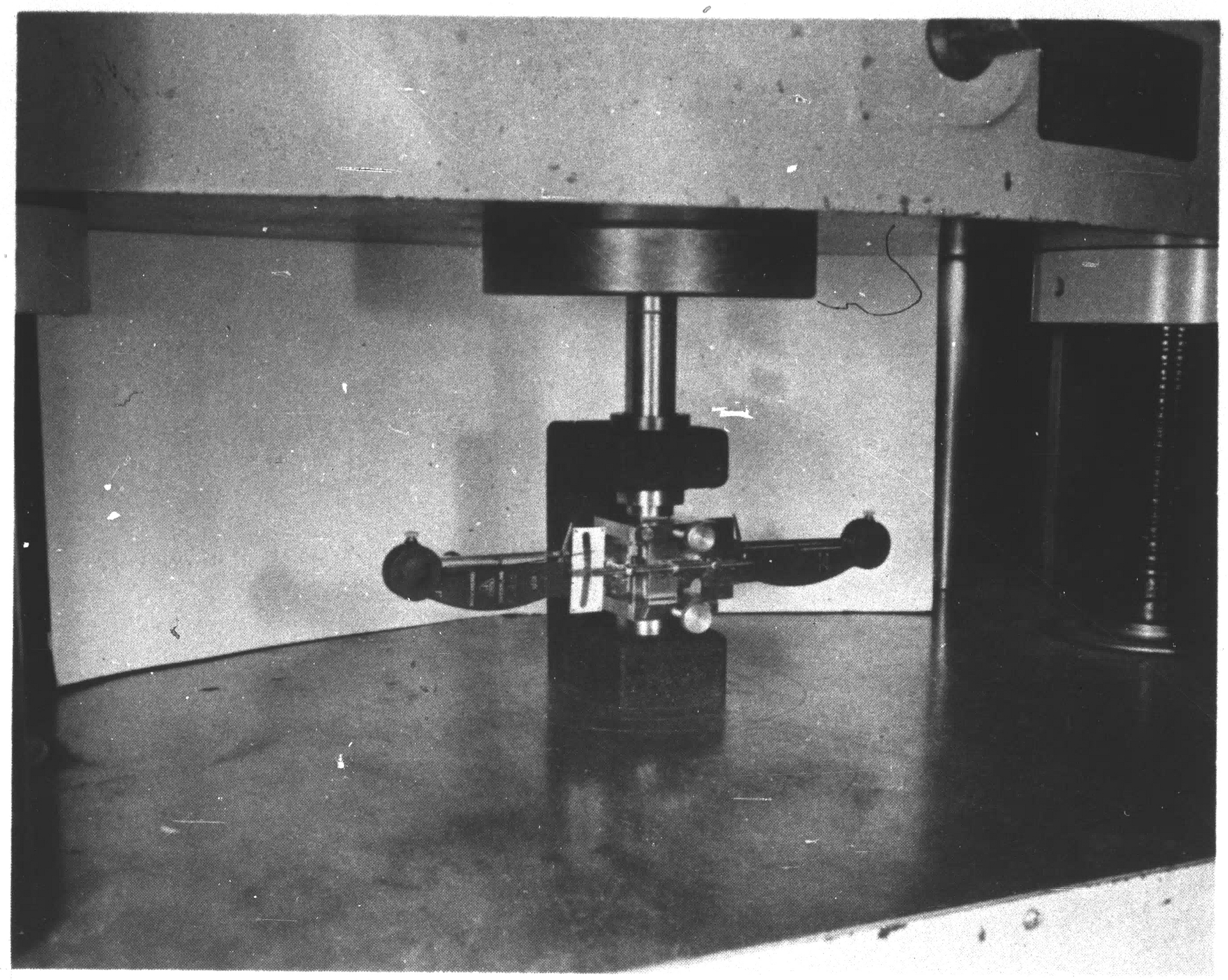


FIG. 18 TEST SET-UP FOR $2\frac{3}{8}$" COUPON

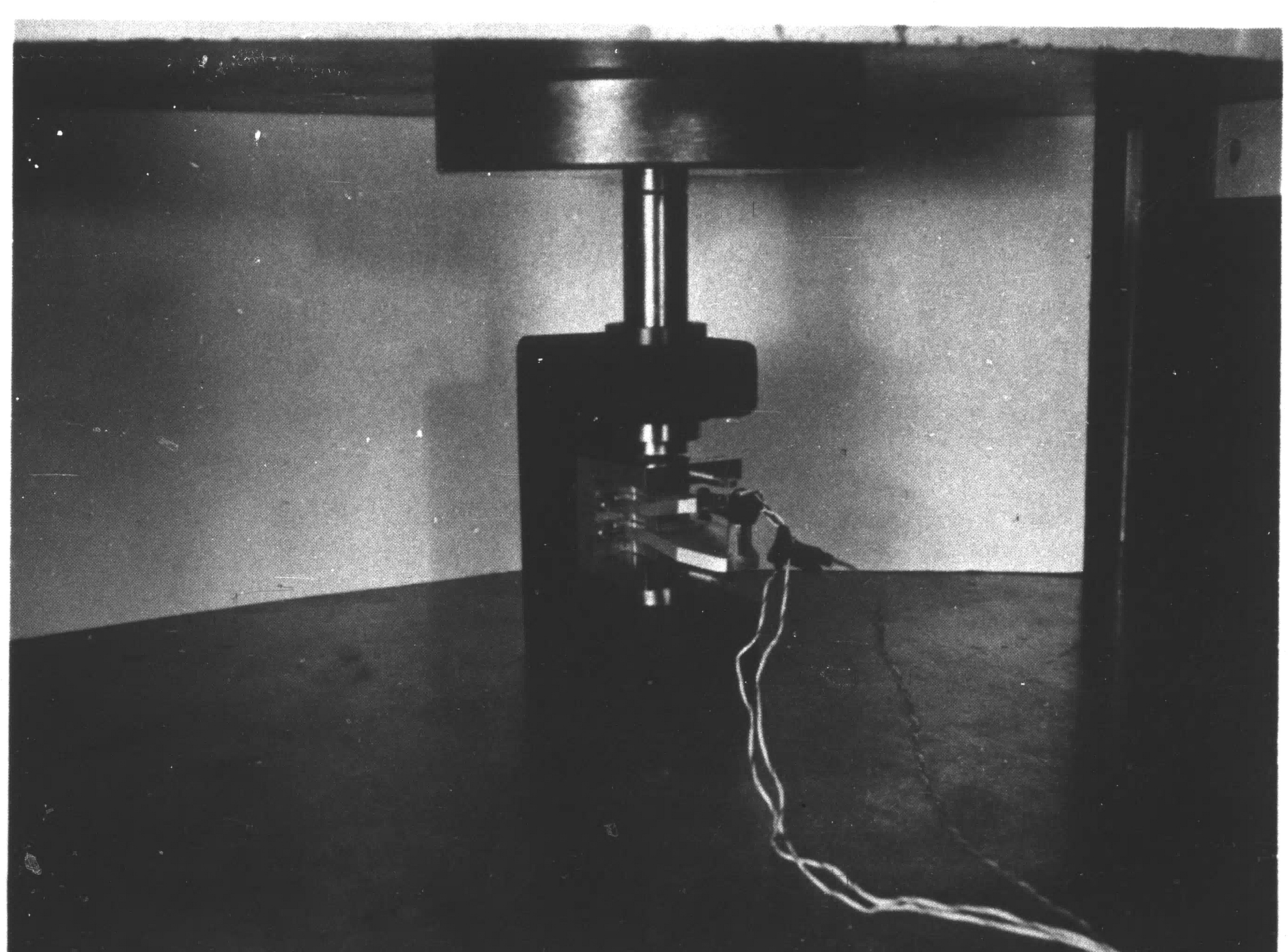


FIG. 19 TEST SET-UP FOR $2\frac{3}{8}$" COUPON

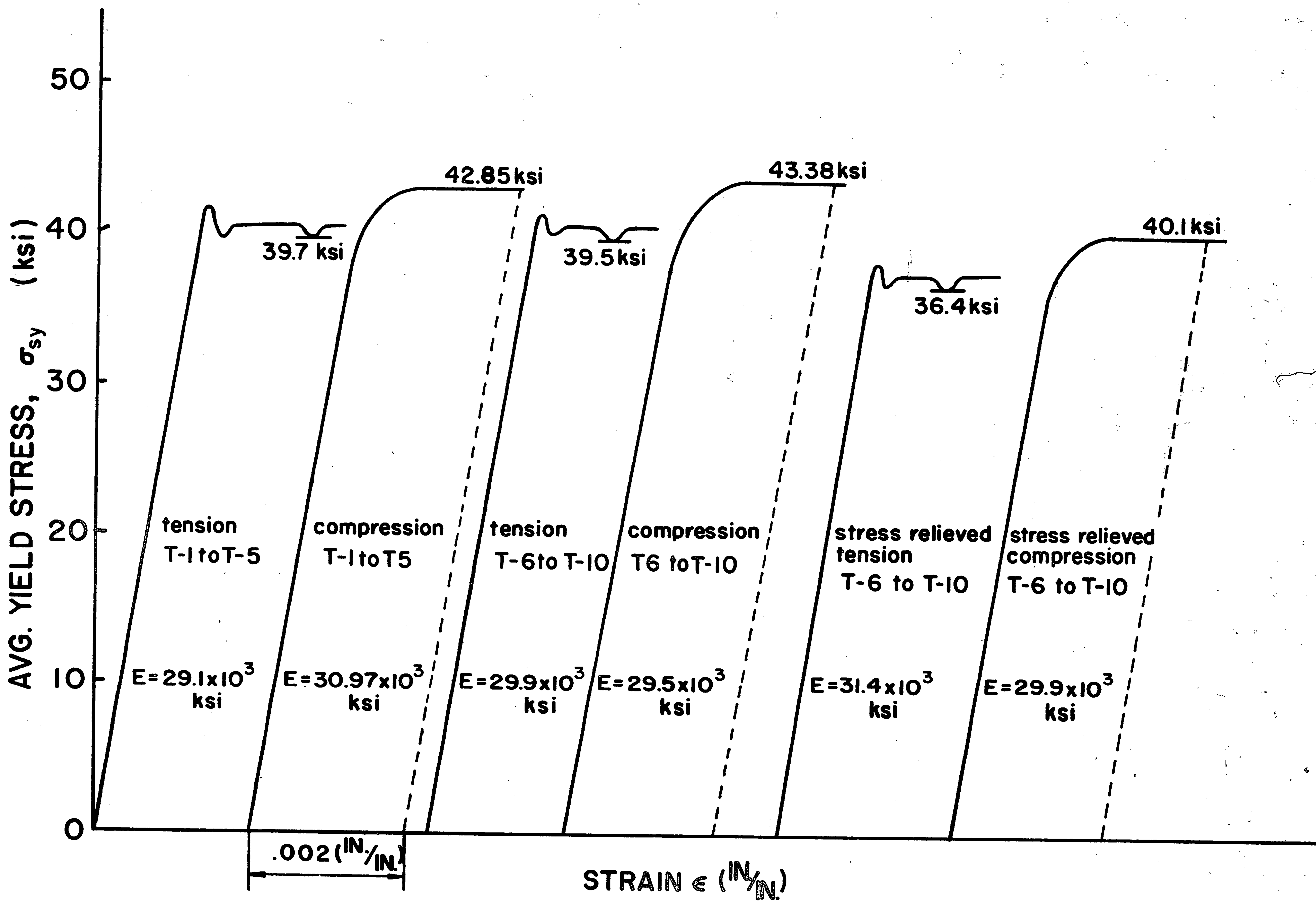


FIG. 20 STRESS-STRAIN CURVE OF AVG. VALUES, PLATES

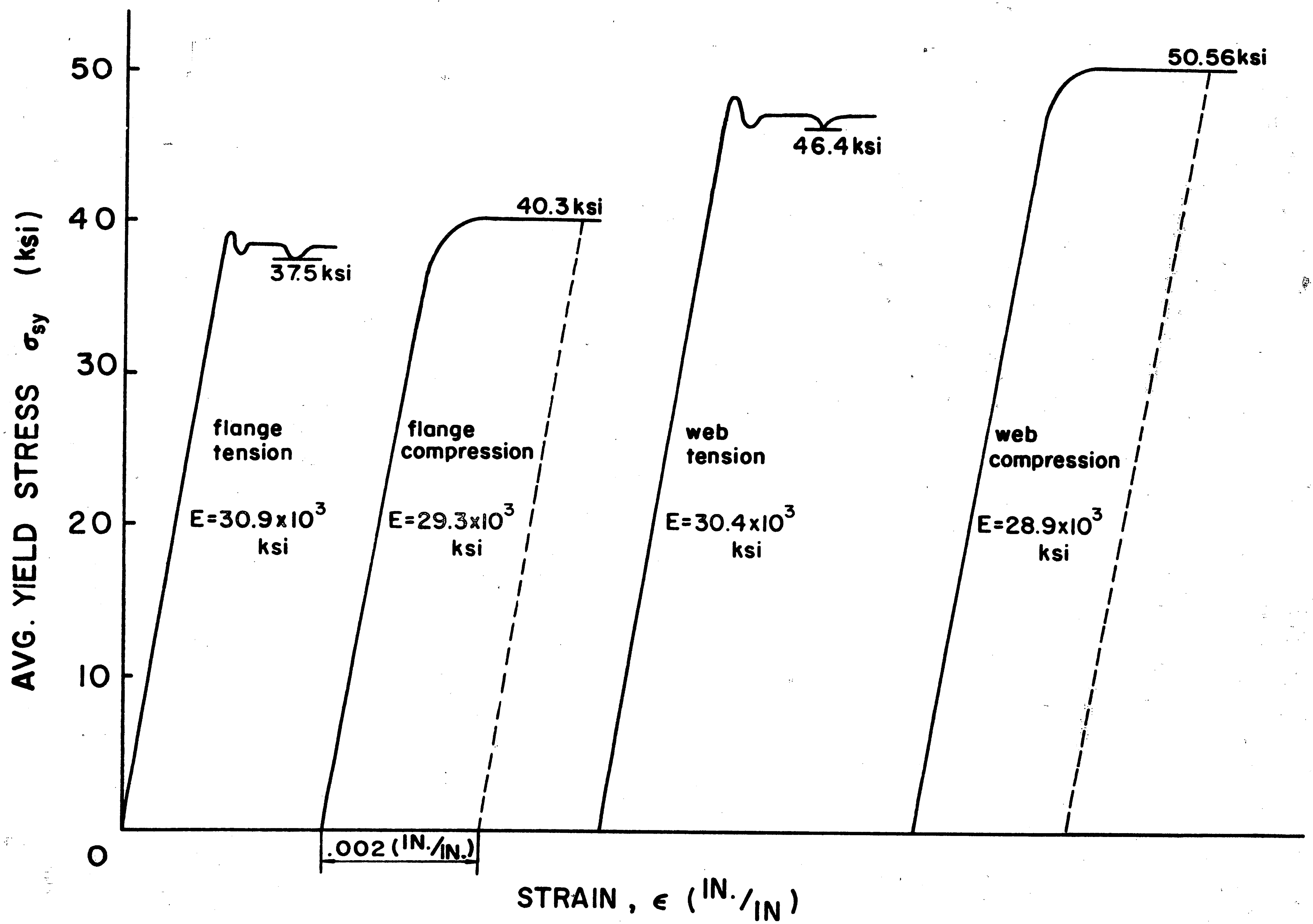


FIG. 21 AVG. STRESS - STRAIN CURVES, ST3B4.25 COUPONS

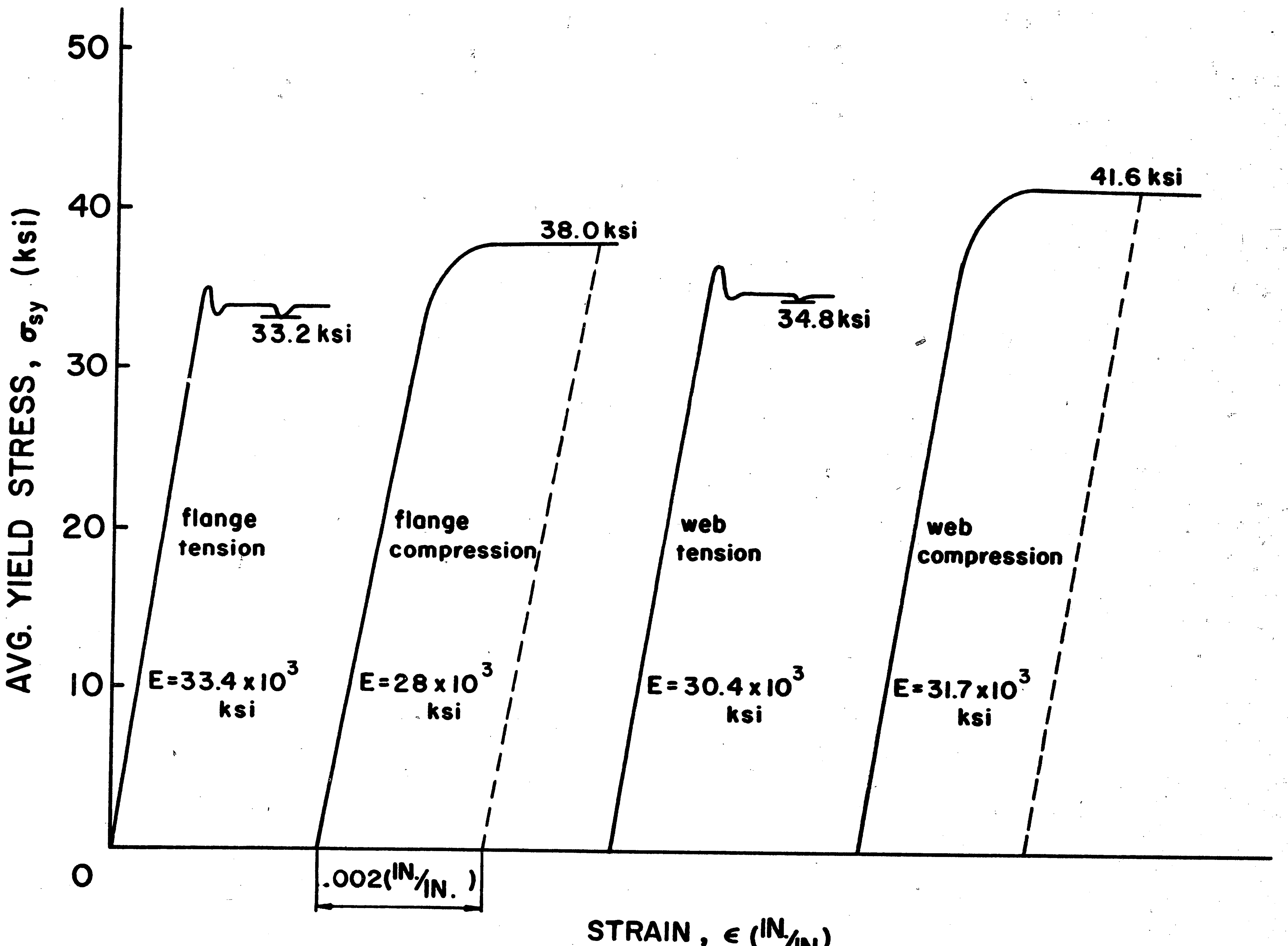


FIG.22 AVG. STRESS – STRAIN CURVES, 6 Jr. 4.4 COUPONS

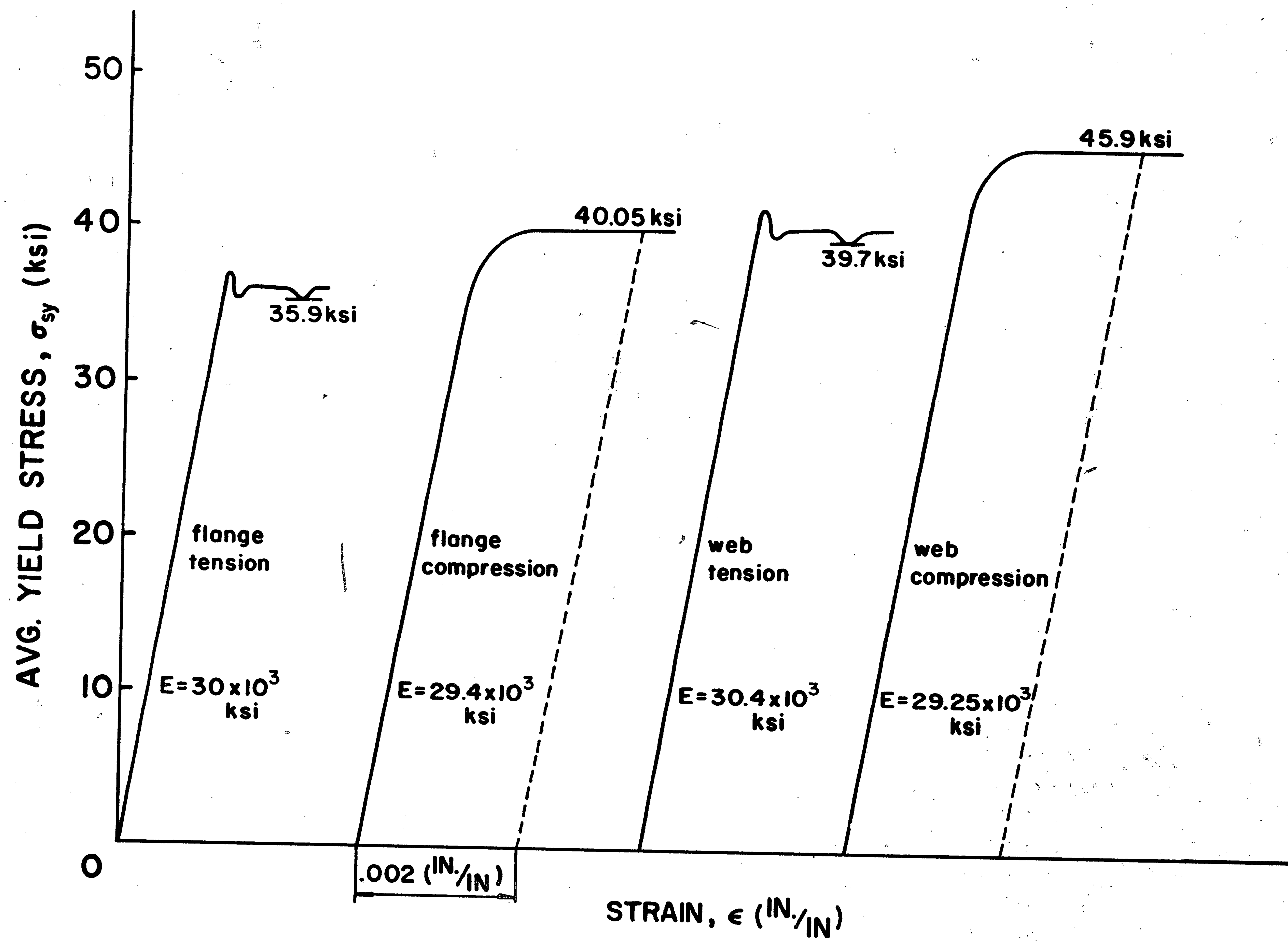


FIG. 23 AVG. STRESS-STAIN CURVES, 6 Jr. 4.4 COUPONS

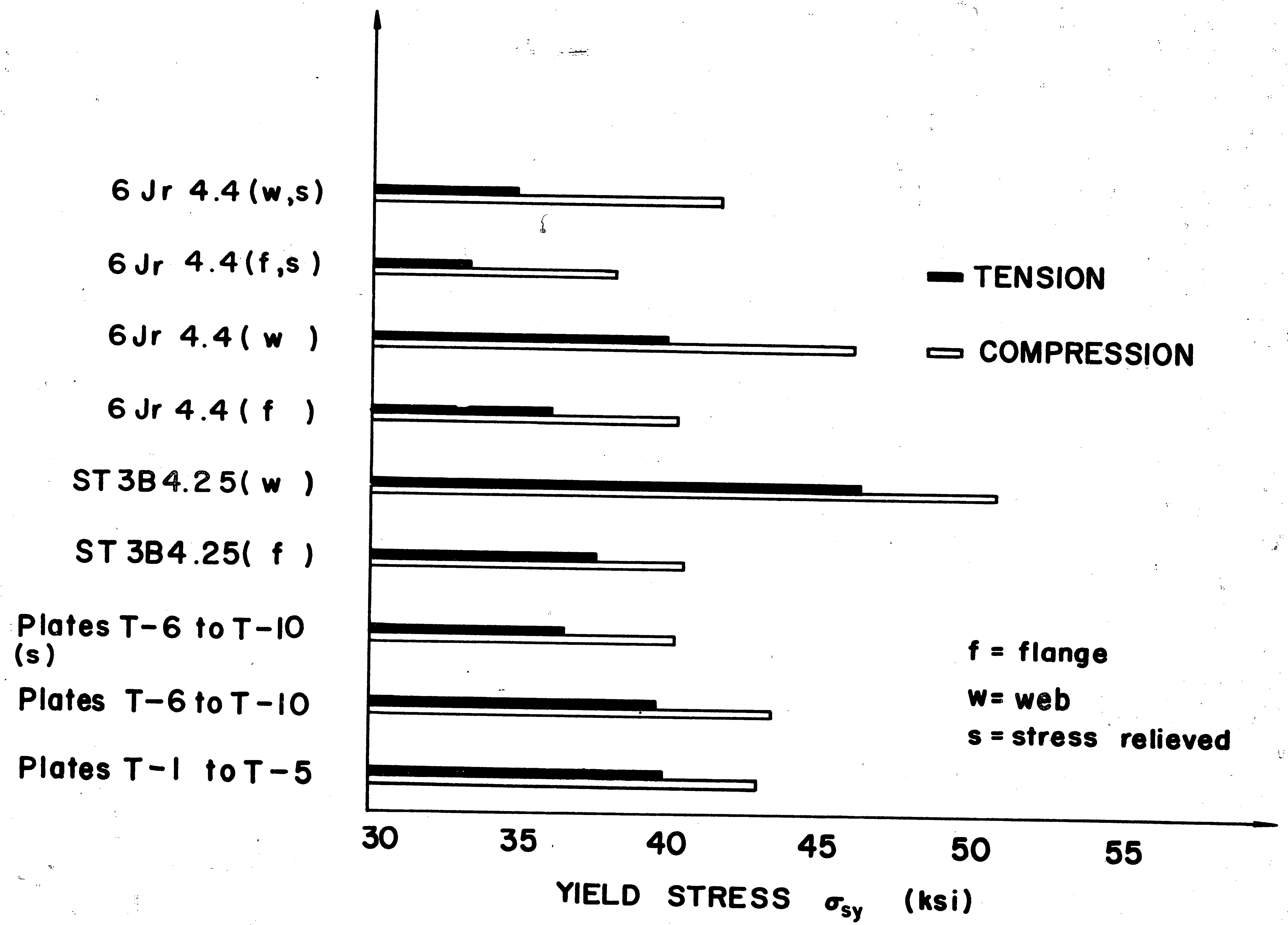


FIG.24 AVERAGE VALUES OF YIELD STRESS

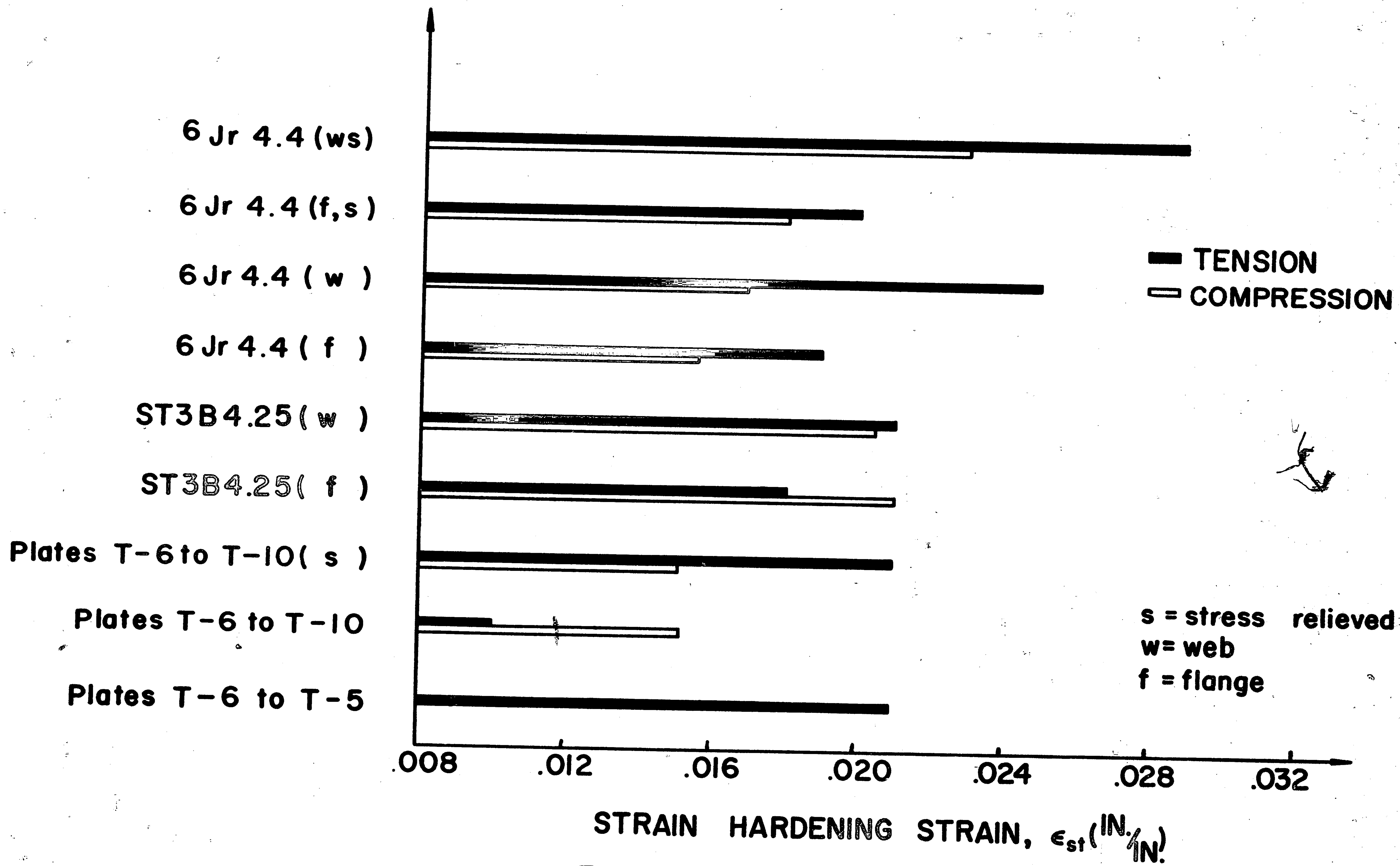


FIG.25 AVG. STRAIN HARDENING STRAIN

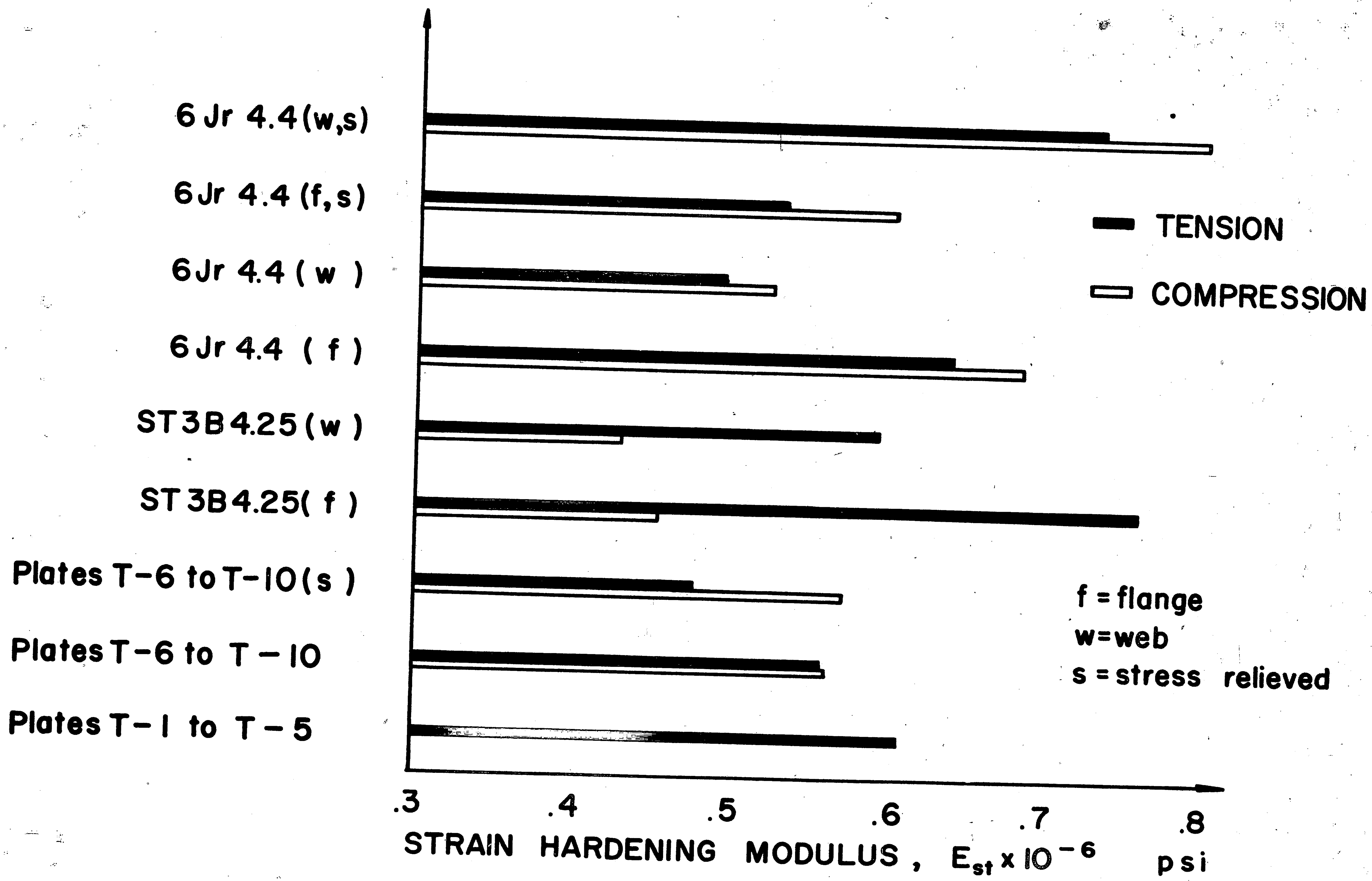


FIG. 26 AVG. STRAIN HARDENING MODULUS

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